PB90-266727

Assessing UST Corrective Action Technologies: Early Screening of Clean-up Technologies for the Saturated Zone

Camp, Dresser and McKee, Inc., Boston, MA

Prepared for:

Environmental Protection Agency, Cincinnati, OH

Jun 90

U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

Risk Reduction Engineering
Laboratory
Cincinnati OH 45268

EPA/600/2-90/027
June 1990

PB90-266727

Research and Development

EPA

Assessing UST Corrective Action Technologies:

Early Screening of Clean-up Technologies for the Saturated zone

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before complet

1. REPORT NO. EPA/600/2-90/027	2.	3. PB90-266727

4. TITLE AND SUBTITLE
ASSESSING UST CORRECTIVE ACTION TECHNOLOGIES:
Early Screening of Clean-up Technologies for
the Saturated Zone.

5. REPORT DATE

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Patrick J. Reidy, Warren J. Lyman and David C. Noonan

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Camp Dresser & McKee Inc.
Boston, MA 02108

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
68-03-3409

12. SPONSORING AGENCY NAME AND ADDRESS
Risk Reduction Engineering Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

13. TYPE OF REPORT AND PERIOD COVERED
Project Report: 6/88-2/90

14. SPONSORING AGENCY CODE
EPA/600/14

15. SUPPLEMENTARY NOTES
FTS 340-6924
Project Officer: Chi-Yuan Fan (201) 906-6924

16. ABSTRACT

This manual assists the user in making a preliminary evaluation of the likely effectiveness of various remediation technologies in the event of a release of petroleum products into the saturated zone. The manual: 1) helps the user develop a conceptual understanding of site conditions before extensive field studies are completed; 2) discusses remediation goals; 3) identifies and helps the user evaluate technologies capable of meeting remediation goals; and 4) discusses follow-up measures.

To help the user develop a conceptual understanding of the site (i.e., conduct a preliminary site assessment) the manual shows how to collect basic information about the subsurface environment and the released product. The manual also provides default values for some parameters if field data are not available or have not yet been collected. The user is then assisted in making a preliminary determination of the likely phase partitioning and mobility of petroleum products in the saturated zone. The three "phases" considered in this manual are: 1) non-aqueous phase liquid (NAPL); 2) dissolved in groundwater; and 3) sorbed to soil particles.

To facilitate the screening process, worksheets are provided to aid in evaluation of the alternative technologies. For each worksheet, factors critical to the successful implementation of a given technology are presented.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 135
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

EPA/600/2-90/027
June 1990

ASSESSING UST CORRECTIVE ACTION TECHNOLOGIES:

Early Screening of Clean-up Technologies for the Saturated Zone

By

Patrick J. Reidy
Warren J. Lyman
David C. Noonan
Camp Dresser & McKee Inc.
Boston, Massachusetts 02108

CONTRACT NUMBER 68-03-3409

Project Officer

Chi-Yuan Fan
Superfund Technology Demonstration Division
Risk Reduction Engineering Laboratory
Edison, New Jersey 08837

RISK REDUCTION ENGINEERING LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45286

DISCLAIMER

The information in this document has been funded by the U.S. Environmental Protection Agency under Contract 68-03-3409 to CDM Federal Programs Corporation. It has been subjected to the Agency's peer and administrative review, and has been approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural resources to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

An area of major concern is the health impacts associated with uncontrolled releases of petroleum hydrocarbons from underground storage tanks. This document focuses on remediation of petroleum product contamination of the saturated zone.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

This manual assists the user in making a preliminary evaluation of the likely effectiveness of various remediation technologies in the event of a release of petroleum products into the saturated zone. The manual: 1) helps the user develop a conceptual understanding of site conditions before extensive field studies are completed; 2) discusses remediation goals; 3) identifies and helps the user evaluate technologies capable of meeting remediation goals; and 4) discusses follow-up measures.

To help the user develop a conceptual understanding of the site (i.e., conduct a preliminary site assessment) the manual shows how to collect basic information about the subsurface environment and the released product. The manual also provides default values for some parameters if field data are not available or have not yet been collected. The user is then assisted in making a preliminary determination of the likely phase partitioning and mobility of petroleum products in the saturated zone. The three "phases" considered in this manual are: 1) non-aqueous phase liquid (NAPL); 2) dissolved in groundwater; and 3) sorbed to soil particles.

The overall focus of the manual is on making a preliminary screening of what saturated zone treatment technologies would likely be effective at a given release site. To facilitate the screening process, worksheets are provided to aid in evaluation of the alternative technologies. For each worksheet, factors critical to the successful implementation of a given technology are presented. For each factor, the site conditions which favor success as well as inhibit success are presented. The worksheets can be compared to screen those technologies most likely to be effective at a given site.

CONTENTS

Foreword iii
Abstract iv
Figures vi
Tables vii
Acknowledgement viii
Abbreviations and Symbols ix

1. Introduction 1
    Background 1
    Purpose 3
    Limitations 5
    Scope 6
    Approach and Organization 6

2. How to Conduct a Site Assessment 10
    Introduction 10
    Gathering Release Information 11
    Gathering Site-Specific Information 13
    Gathering Contaminant-Specific Information 21
    Evaluating Contaminant Phases 28
    Evaluating Contaminant Mobility 39
    Setting Remediation Goals 48

3. Technology Selection 53
    Introduction 53
    Containing NAPL and/or Dissolved Contaminant........ 55
    Recovery of Floating NAPL 65
    Treatment of Contaminants Dissolved in Groundwater ... 72
        Above-ground Treatment 72
        In-situ Treatment 82
    New Technologies 87
    Technology Compatibility 88

4. Follow-up Measures 91
    Re-Evaluate Remediation Goals 91
    Monitoring Technical Performance 91

References 96

Appendices

A How to Use the Worksheets 99

Glossary 111
Blank Worksheets 116

FIGURES

Number Page

1 Three Phases In Which Petroleum Products Can be Found In Saturated Zone 2

2 Progression of a Typical Release Through the Subsurface 4

3 An Overview of the Approach 8

4 Groundwater Temperatures in the United States 18

5 Potential Exposure Pathways of Contaminants in the Saturated Zone 20

6 Apparent Versus True Thickness of Floating NAPL 31

7 Ratio of Apparent to True NAPL Thickness 33

8 The Effect of Density on Contaminant Plume Migration 41

9 Examples of Poorly Designed Monitoring and Recovery Wells ... 42

10 Seasonal Variations in Groundwater Flow 44

11 Variability of Subsurface Stratigraphy 46

12 Inter-Aquifer Contaminant Transport 47

13 Density-to-Viscosity Ratios for Water and Hydrocarbons 49

14 Estimating Groundwater Travel Time 50

15 Schematic Diagram of Trench Excavation 56

16 Typical Pumping Well Installation for Containment of NAPL and/or Dissolved Contaminant 60

17 Effect of Hydraulic Conductivity Differences on the Area of Influence of Pumping Wells 61

18 Single and Dual Pump Recovery Systems 67

19 Schematic Diagram of a Vacuum Extraction System 69

20 Retention of Dissolved Contaminants in Less Permeable Formations 74

21 Schematic Diagram of a Packed Tower Air Stripper 77

22 Typical In Situ Biorestoration System 84

TABLES

Number		Page
1	Basic Release Information Assumed to be Known	12
2	Site-Specific Parameters	15
3	Physicochemical Properties of Rocks and Soil	16
4	Relationship Between Diameter of Particles and Surface Area	17
5	Contaminant-Specific Parameters	23
6	Unweathered Composition of Three Common Hydrocarbon Mixtures	24
7	Physicochemical Properties of Five Common Hydrocarbon Mixtures	26
8	Physicochemical Properties of Individual Hydrocarbon Constituents	27
9	Refractory Index for Common Hydrocarbon Compounds	29
10	Likelihood of Liquid Contaminants Being Present on the Water Table	35
11	Likelihood of Dissolved Contaminants Being Present in Groundwater	36
12	Worksheet to Evaluate the Feasibility of Trench Excavation	58
13	Worksheet to Evaluate the Feasibility of Pumping Wells	63
14	Worksheet To Evaluate the Feasibility of Vacuum Extraction for Floating NAPL Recovery	71
15	Worksheet for Evaluating the Feasibility of Air Stripping Being Effective at Your Site	78
16	Worksheet for Evaluating the Feasibility of Carbon Adsorption Being Effective at Your Site	81
17	Worksheet for Evaluating the Feasibility of Biorestoration Being Effective at Your Site	85
18	Compatibility of Saturated Zone and Unsaturated Zone Technologies	90

ACKNOWLEDGEMENTS

This manual was produced by Camp Dresser & McKee Inc. (CDM) under the supervision of Dr. Myron S. Rosenberg as a work product associated with Work Assignment No. 107 under Contract 68-03-3409 with EPA's Office of Research and Development (ORD).

CDM would like to acknowledge the guidance and assistance provided by Mr. Anthony N. Tafuri, ORD's Project Officer, and Mr. Chi-Yuan Fan, ORD's Technical Project Monitor for this Work Assignment. CDM also appreciates the help provided by Ms. Iris Goodman of EPA's Office of Underground Storage Tanks in developing the overall focus of the manual.

Dr. Warren Lyman, Mr. David Noonan and Mr. Patrick Reidy of CDM prepared this manual. Research and scientific evaluations that form the basis of this manual were developed by Dr. Lyman and Mr. William Thompson of PEI Associates, Inc., and were initiated and guided by Mr. John Farlow of ORD. Mr. Roland Robinson, assisted by Ms. Catherine Hooper, prepared the manuscript, and Mr. A. Russell Briggs prepared the graphics.

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

API — American Petroleum Institute
CDM — Camp Dresser & McKee Inc.
CSF — critical success factor
EPA — Environmental Protection Agency
ORD — EPA's Office of Research & Development
RREL — EPA's Risk Reduction Engineering Laboratory
TOC — total organic carbon
USGS — United States Geological Survey
UST — underground storage tank
WSF — water soluble fraction
ZOC — zone of contribution
cm/sec — centimeters per second
cP — centipoise
cm/day — centimeters per day
in/yr — inches per year
g/cm^3 — grams per cubic centimeter
g/m^3 — grams per cubic meter
gpm — gallons per minute
m^2/g — meters square per gram
mg/L — milligrams per liter
mm Hg — millimeters of mercury
L/kg — liters per kilogram
ppm — parts per million
ppb — parts per billion

SYMBOLS

°C — degrees Celsius
g — gram
cm — centimeter
mm — millimeter
L — liter
gal — gallon
ft — feet
mo — month
yr — year
% — percent
Hg — mercury
C — concentration of contaminant in ground water [mg/L]
K_d — distribution coefficient
K_{oc} — soil/water partitioning coefficient
K_{ow} — octanol/water partitioning coefficient
pH — indicates alkaline or acid conditions in log units
RI — refractory index

SECTION 1

INTRODUCTION

BACKGROUND

The release of petroleum products into the environment has become a growing concern over the years. Of particular concern is contaminant movement into the subsurface, where valuable groundwater and connected surface water resources are at risk. Awareness of the problem has resulted in the development and use of a variety of remediation techniques to remove petroleum products from the subsurface.

An effective response to a release of petroleum products requires understanding site conditions and defining appropriate remediation goals. These vary from site to site and can range from no immediate action to removal of all petroleum product contamination from the subsurface. Selecting the technology or technologies that best meets these goals involves identifying potential impacts to the surrounding environment, recognizing the regulatory restrictions that may govern clean-up criteria, and evaluating the likely effectiveness of alternative technologies.

To adequately address the problems associated with a release, those responsible for remediation efforts must be well informed. This manual: 1) shows the user how to develop a conceptual understanding of site conditions; 2) discusses various remediation goals that may be best suited to a given site; 3) identifies the alternative technologies that address the problem; and 4) provides a means to evaluate the likely effectiveness of the technologies.

The focus of this manual is on technologies designed specifically for clean up of the saturated zone and covers only remediation of contaminants known to have reached the water table. In this manual, the saturated zone is defined as the zone below the ground surface in which all pore spaces are filled with water. Contamination reaching the saturated zone is typically only a fraction of the total mass released, but the associated costs are often greater than for treatment of the unsaturated zone. Petroleum products reaching the saturated zone are subject to greatly increased mobility of the contaminant, particularly in the horizontal direction. Mobilization of the contaminants increases the magnitude of clean-up efforts and the opportunity for liability.

Research done for EPA's RREL Office in Edison, New Jersey identified 13 different conditions under which contaminants released to the subsurface as bulk petroleum product could be found (EPA, 1988a). However, most of the released product will exist in only a few of these phases. For simplicity, this manual assumes that petroleum products found in the saturated zone exist almost exclusively in three phases: 1) non-aqueous phase liquid (NAPL); 2) dissolved in groundwater (dissolved phase); and 3) sorbed to soil particles (solid phase). Figure 1 is a schematic diagram showing each of the three saturated zone phases covered in the manual.

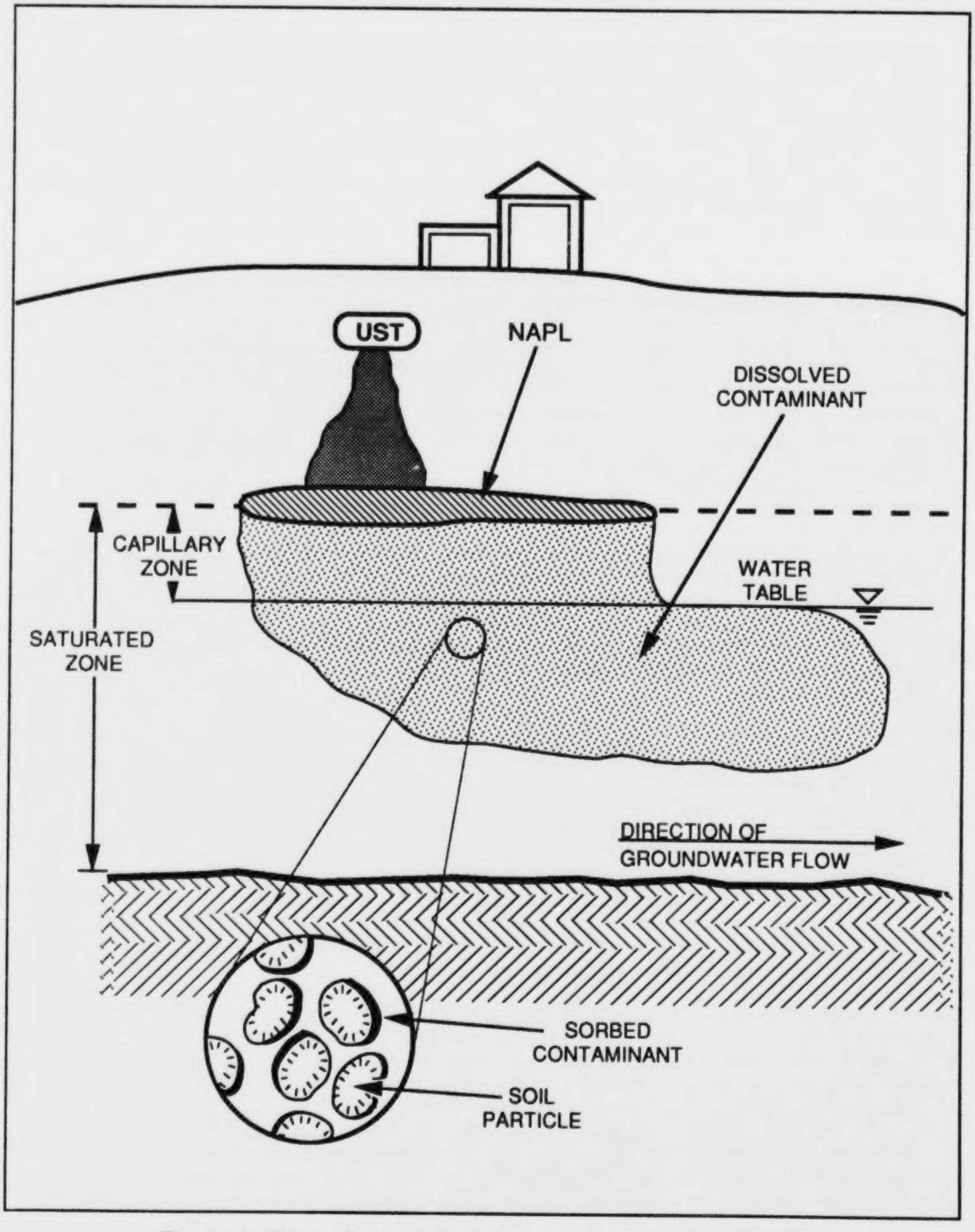

UST
NAPL
DISSOLVED CONTAMINANT
CAPILLARY ZONE
WATER TABLE
SATURATED ZONE
DIRECTION OF GROUNDWATER FLOW
SORBED CONTAMINANT
SOIL PARTICLE

Figure 1. Three Contaminant Phases in the Saturated Zone

When petroleum products are released into the subsurface, they move primarily by gravity down through the unsaturated zone, with only minor horizontal movement (away from the release source) due to dispersion and capillary forces. As the plume encounters the capillary zone above the water table, the weight of the plume depresses first the capillary zone and then the water table. The upward buoyancy forces of the groundwater slow the downward movement of the leading edge of the plume, forcing the contaminant to move horizontally in all directions. The liquid product forms a pancake shape on top of the water table as the remainder of the plume is drawn downward by gravity. If the release is terminated, the trailing edge of the plume will reach the water table and eventually a quasi-equilibrium is reached. The floating plume will then be confined to horizontal flow, usually in the same direction as local groundwater. Figure 2 shows a typical sequence of events in the first stages of a release as they relate to the saturated zone.

After the bulk product has reached the water table, its liquid density determines for the most part how the NAPL will move vertically in the saturated zone. If heavier (more dense) than water, the bulk product will sink through the saturated zone until it reaches a barrier. Most petroleum products are lighter than water, and bulk product will tend to float on the surface of the water table. However, some lighter than water product can still find its way below the water table. As the force exerted by the contaminant plume depresses the water table, groundwater around the plume tends to rise or mound and equilibrium is lost. (A larger mass of free product will cause a greater mounding effect than a smaller one.) The groundwater then seeks to re-establish its equilibrium and may enclose part of the free product plume, trapping NAPL below the water table that might normally be expected to float. NAPL can also end up below the groundwater table in areas with fluctuating groundwater levels (e.g., due to infiltration events or tides), or due to burial by freshly infiltrating water. NAPL trapped below the water table can present recovery problems.

Described herein are several technologies which are currently widely used or show potential for success in removing contaminants from the saturated zone. In addition, the manual assists the user in determining when a technology is likely to be effective and, perhaps more importantly, when it is not.

PURPOSE

The intended users of the manual are state and local officials responsible for overseeing remediation or monitoring of releases of petroleum products in the saturated zone, including leaking underground storage tanks (USTs). These officials can use the manual to screen alternatives prior to collection of extensive field data. The knowledge gained will help the regulators work with the responsible party to develop a well-focused field program and better guide the early stages of remediation.

By using this manual, screening of technologies can be accomplished at relatively low cost and within a short time (approximately one to two weeks). The savings in time and cost are realized by estimating many of the parameters needed to characterize a site. The tables, figures and

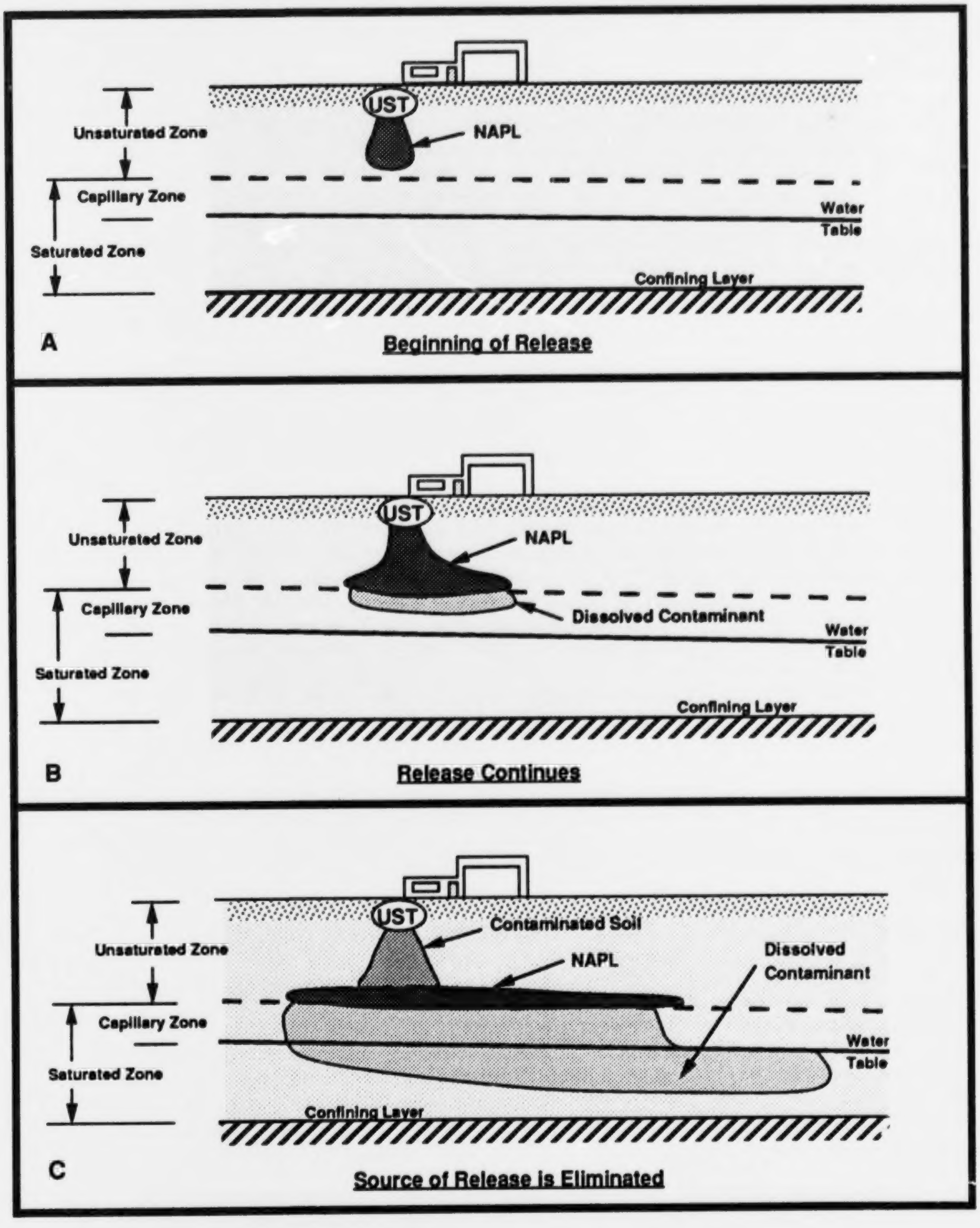

UST
NAPL
Unsaturated Zone
Capillary Zone
Saturated Zone
Water Table
Confining Layer
A
Beginning of Release
UST
NAPL
Dissolved Contaminant
Unsaturated Zone
Capillary Zone
Saturated Zone
Water Table
Confining Layer
B
Release Continues
UST
Contaminated Soil
NAPL
Dissolved Contaminant
Unsaturated Zone
Capillary Zone
Saturated Zone
Water Table
Confining Layer
C
Source of Release is Eliminated

Figure 2. **Progression of a Typical Petroleum Product Release from an Underground Storage Tank**

explanatory text in this manual help the user estimate these parameters and complete a site assessment. As used in this manual, a site assessment is analogous to developing a conceptual understanding of a site so that a working hypothesis can be made of how the petroleum products will behave in the subsurface and the impact of the release on the environment. The site assessment will typically be based on readily available data, but can and should be enhanced with field measurements.

It is important to distinguish between the estimated characterization of a site under a preliminary site assessment and an actual characterization based on extensive field studies. A site assessment uses estimates of many site-specific parameters, and the more parameters that are estimated, the less accurate will be the understanding of actual site conditions. Nonetheless, the manual can be used to help produce a reasonably accurate characterization of the site, define reasonable clean-up goals, and identify those technologies most likely to be effective in achieving the clean-up goals.

LIMITATIONS

Users of the manual should be aware of the following limitations of the document.

- This is Not a Design Manual - This document is not intended to be a design manual for engineers whose primary goal is final technology selection and design. Rather, it is intended as a pre-design or pre-selection manual more suited to a preliminary screening of alternatives likely to be effective.

- Saturated Zone Coverage Only - This document addresses contaminant releases that are known or assumed to have reached the saturated zone. It does not cover the unique problems associated with remediation of the unsaturated zone. Technical guidance in evaluating other stages of remediation can be found in the companion Unsaturated Zone document, among other sources.

- Not for Emergency Response - The comprehensive clean-up of an UST involves several stages of remediation. First among these are emergency measures involving tank removal and response to any potentially explosive conditions resulting from the leak. These measures are assumed to have been addressed prior to initiation of saturated zone assessment.

- Evaluation is Scientifically Based - Evaluation of the various clean-up technologies presented in this manual is based primarily on scientific and engineering related factors. Other considerations, such as cost or equipment availability, are often very important in assessing and selecting a technology. The user should be aware of such considerations when assessing a site.

- Focus on Petroleum Hydrocarbons as Contaminants - Because petroleum products are the most common materials stored in USTs, petroleum is targeted as a contaminant in this manual. However, this does not preclude the use of the approach of the manual in evaluating other types of contaminants.

- Clean-up Goals Can Only be Addressed Qualitatively - Technology selection is usually based on what clean-up goals must be achieved. It is beyond the scope of this manual to define what clean-up goals should be set at each site. Rather, a qualitative discussion is provided that raises the issues that are important in setting up clean-up goals and defining "how clean is clean."

SCOPE

The following items provide an overview of the principal components of the manual.

- For each treatment technology a unique set of factors (critical success factors or CSFs) plays a major role in the success or failure of the technology at a given site. For each technology covered in this manual, important CSFs are identified that should be considered when evaluating a site.
- The user is aided in developing a conceptual understanding of site conditions and in evaluating the contaminant in the three chemical phases discussed in this manual: 1) non-aqueous phase liquid (NAPL); 2) dissolved in groundwater, and 3) sorbed to the soil.
- Several technologies are presented that have proved successful, or shown promise of being successful, and worksheets are provided to assist in evaluating the technologies.
- Procedures to quickly assess the advantages and disadvantages of the technologies without conducting extensive and costly field studies are presented.

APPROACH AND ORGANIZATION

The manual is designed to be understandable to a user without an extensive technical background. Therefore, a simplified, yet scientifically-based, approach to assessing petroleum releases and evaluating clean-up technologies is used. The approach emphasizes posing and answering the types of questions that should be asked when confronted with removing contaminants from the saturated zone.

Some aspects of a site assessment require a rather complex evaluation process, making it difficult to obtain quantifiable results. These are dealt with in a more qualitative manner without the need of complicated equations or professional expertise. Much of the information required to assess a site can be obtained through the explanatory text, tables, figures, tabulated default values, and worksheets presented in the manual. Examples are provided in the Appendix to demonstrate how to use the worksheets.

Figure 3 shows an overview of the basic components of the approach used in the manual: 1) site assessment; 2) technology screening; and 3) follow-up measures. Each is briefly discussed below.

Site Assessment

Section 2 helps the user develop a conceptual understanding of overall site conditions by:

- showing the user what information is required and ways it can be obtained;
- helping the user estimate the mobility of the contaminant in the saturated zone (how quickly the contaminant moves through the subsurface);
- helping the user estimate the degree of partitioning of contaminant in the saturated zone (how much of the contaminant is likely to be in each of the three phases); and
- discussing the various types of remediation goals that might be appropriate at a given site.

Technology Screening

After a conceptual understanding of site conditions has been developed, but prior to screening of alternative technologies, the user should decide on the most appropriate first course of action (i.e., set remediation goals). This decision will guide the beginning stages of remediation. Section 3 presents various technologies that are applicable to remediation of the saturated zone. As Figure 3 shows, the section is organized so that technologies best suited to a particular remediation goal are grouped together and can be easily compared. Factors that influence the overall effectiveness of each technology are identified in worksheets, which can be used to aid in screening the technologies.

More than one technology may be required at a site to improve overall remediation. However, not all technologies are compatible when used in combination. Included at the end of Section 3 is a brief discussion of which technologies are more or less compatible.

Follow-up Measures

Follow-up measures are an important aspect of overall remediation, particularly since remediation often involves several different stages or phases that are implemented over an extended time period. This manual offers a method of quickly pre-screening alternatives as a first response to a petroleum product release. Further stages of remediation can also be examined using this manual once secondary goals have been defined. This is illustrated in Figure 3. For example, the most immediate goal of remediation may be to prevent off-site migration of dissolved contaminants. Urgency may dictate that this phase begin prior to finalizing all stages of remediation. At a later time additional goals may be defined that can be examined the same way the initial goal was.

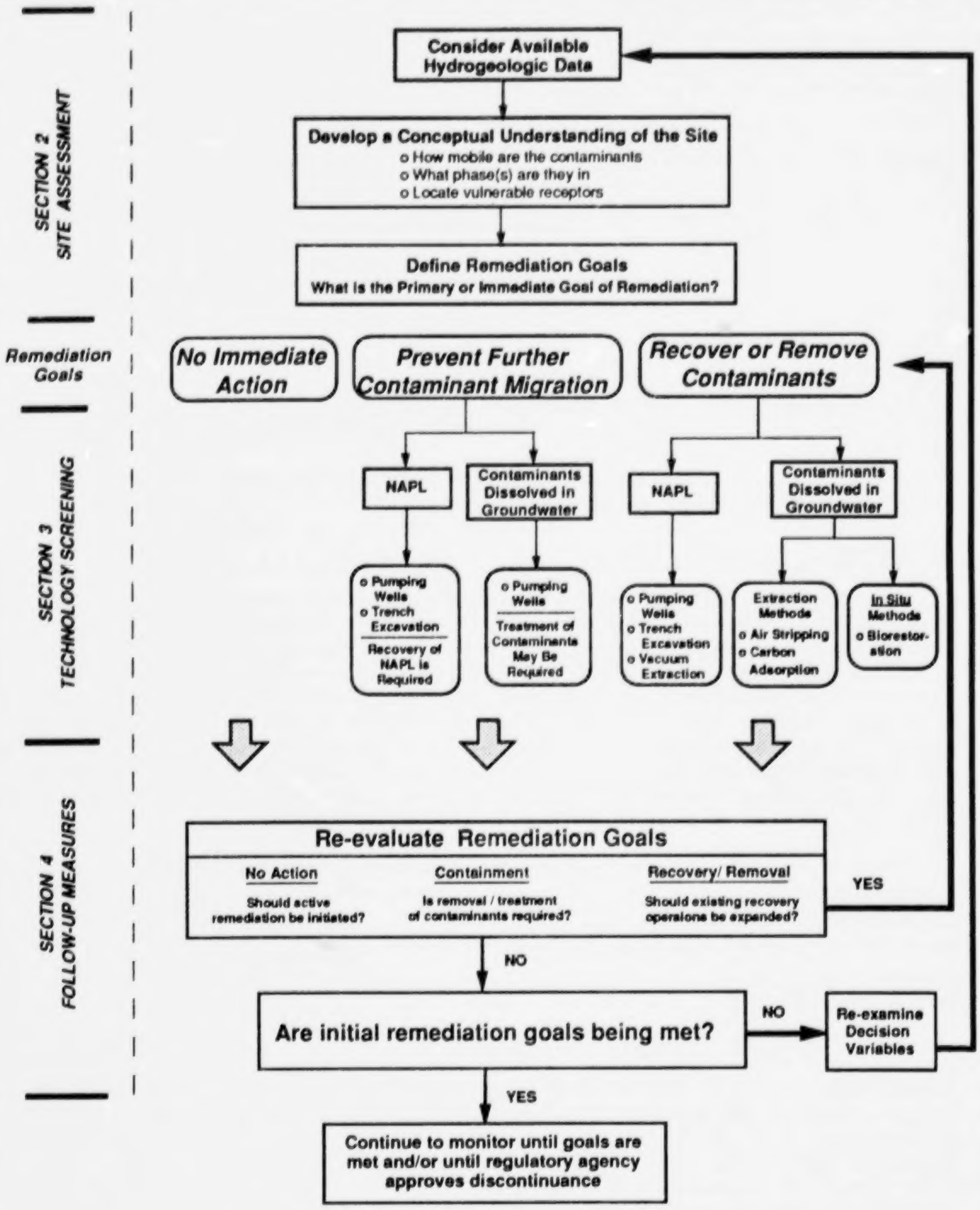

SECTION 2
SITE ASSESSMENT
Remediation Goals
SECTION 3
TECHNOLOGY SCREENING
SECTION 4
FOLLOW-UP MEASURES
Consider Available Hydrogeologic Data
Develop a Conceptual Understanding of the Site
o How mobile are the contaminants
o What phase(s) are they in
o Locate vulnerable receptors
Define Remediation Goals
What is the Primary or Immediate Goal of Remediation?
No Immediate Action
Prevent Further Contaminant Migration
Recover or Remove Contaminants
NAPL
Contaminants Dissolved in Groundwater
NAPL
Contaminants Dissolved in Groundwater
o Pumping Wells
o Trench Excavation
Recovery of NAPL is Required
o Pumping Wells
Treatment of Contaminants May Be Required
o Pumping Wells
o Trench Excavation
o Vacuum Extraction
Extraction Methods
o Air Stripping
o Carbon Adsorption
In Situ Methods
o Biorestoration
Re-evaluate Remediation Goals
No Action
Should active remediation be initiated?
Containment
Is removal / treatment of contaminants required?
Recovery/ Removal
Should existing recovery operaions be expanded?
YES
NO
Are initial remediation goals being met?
NO
Re-examine Decision Variables
YES
Continue to monitor until goals are met and/or until regulatory agency approves discontinuance

Figure 3. An Overview of the Approach

Another important function of site monitoring is to evaluate the success of the technology being used to remediate the site. A given technology may not be successful at a site for a variety of reasons, including a poor understanding of site conditions. Section 4 discusses how to monitor the performance of a technology so that poor performance can be recognized and corrected.

SECTION 2

HOW TO CONDUCT A SITE ASSESSMENT

INTRODUCTION

After emergency measures have been addressed at a site, the first step in a remediation plan should be to gain a general understanding of conditions at the site. The more that is known about the site, the easier it will be to set clean-up goals and select a plan that will effectively achieve these goals. The framework for a typical site assessment is outlined in this section and can be followed to help develop a preliminary "working hypothesis" of site conditions. The assessment should, at a minimum, answer the following questions:

- What contaminants were released? - The type of bulk petroleum product, the constituents comprising the bulk product, and the physical and chemical properties of both the bulk product and its constituents must be known.

- How much of the contaminant remains as free product and how much has dissolved into the groundwater? - Estimating the volume of contaminant aids in understanding subsurface behavior and helps to formulate clean-up goals and assess removal effectiveness during follow-up monitoring.

- How far, how quickly, and in what direction(s) has the contaminant traveled? - The areal and vertical extent and movement characteristics of the contaminant are very important in deciding what course of action is to be taken.

- What receptors are likely to be impacted by the release? - Knowledge of possible impact to receptors (e.g., nearby wells or streams) will determine to a great extent clean-up priorities and short and long term goals.

- What regulatory requirements apply to the site? - Regulatory standards are instrumental in determining the degree of clean-up required and the quality of effluent discharged from treatment processes. These in turn play a large role in developing the goals of remediation and selecting the technologies that will effectively meet those goals.

Answering these questions will give the user a conceptual understanding of site conditions and help guide the initial stages of the remedial clean-up plan. More information can improve the evaluation, but is not essential for a preliminary assessment.

A distinction is made here between bulk product and the individual constituents that make up the bulk product. Examples of bulk product include automotive gasoline, No. 2 fuel oil, and jet fuel. These bulk products, in turn, are composed of hundreds of individual constituents, each with its own set of chemical properties. The individual constituents dissolve in water and evaporate at rates that are somewhat different than the rate of the bulk product. (The chemical properties of the bulk product tend to be a composite of the chemical properties of its individual constituents.) The distinction between bulk product and individual constituents is important because the bulk product will "weather" (break down into its simpler component parts) over time. Further discussion of the distinction between weathered and unweathered product is provided in the subsection on obtaining contaminant-specific information.

An important first step in developing a good conceptual understanding of a site involves collecting data unique to the site in question. Data collection can be grouped into three general categories: 1) release-related; 2) site-related; and 3) contaminant-related. Each of these categories is described in greater detail on the following pages. For a site assessment, these data can, for the most part, be found in tables and figures from various literature sources or through local or regional agencies or offices. The data are used to evaluate contaminant behavior in the subsurface (i.e. where is it, what phase is it in, and where is it going?) and how the contaminants will impact the environment.

The following subsections are structured to help the user collect and evaluate data useful in a site assessment. Tables, figures and relatively simple calculations are presented along with the text to aid in a conceptual understanding of site conditions and in formulating clean-up goals.

GATHERING RELEASE INFORMATION

The initial step in any investigation is to become familiar with the circumstances of the release. Answering the questions in Table 1 provides a familiarity with the site and a foundation for conducting the remainder of the assessment.

What was released? - Knowing what type of petroleum product was released allows a determination of the physical and chemical properties and composition of the contaminant. Often the owner/operator will know the source of the release.

How much was released? - Knowing the volume of contaminant released is important. A very small release may not even reach the saturated zone before attenuation prevents further downward migration, particularly in areas where the depth to groundwater is great. Indications of a very large release should alert responsible parties to engage a clean-up team with the appropriate experience and capabilities. Knowing the size of the release also helps to define clean-up goals and provide a means to measure performance.

For a leaking UST, the time period over which the leak occurred and the flow rate must be estimated, making volume determinations difficult, particularly since the leak rate can vary over time. Often, the best way to estimate the volume of a release is to examine unaccounted-for losses in the records kept by the owner/operator of the tank. These can provide clues as to the volume of the release and when the leak started. These records are not always accurate and may not reflect the actual history of the leak, especially if the problem was known but concealed. But there is

TABLE 1. BASIC RELEASE INFORMATION ASSUMED TO BE KNOWN

INFORMATION NEEDED	WHY INFORMATION IS IMPORTANT
What contaminants were released?	Physical and chemical properties differ for each contaminant, leading to varying phase partitioning, mobility, and degradation characteristics for each contaminant. Corrective action selection is tied to these characteristics.
How much was released?	The amount released directly affects the phases in which the contaminant may be found.
What was the nature of the release (quick spill/slow leak)?	Phase partitioning and mobility of the released contaminant are both affected by the nature of the release. As a result, selection of appropriate corrective actions may differ for quick spills versus leaks over extended period of time.
How long since the release?	Contaminants "weather" over time, that is, change in composition due to processes such as degradation, volatilization, and natural flushing from infiltrating rainfall. This change in composition directly affects the physical and chemical properties of the bulk contaminant.
How was the release detected?	May provide insight into above questions and areal extent and distribution of contamination in the subsurface.

often little else to go on and estimates based on this type of data must suffice. Additionally, the owner/operator may have results of tank tightness tests for the leaking UST that may provide clues as to the likely rate of the release.

What was the nature of the release? - The nature of the release refers to how and when the contaminant was released to the environment. Was it a large release over a relatively short time span (a quick spill) or did small amounts of product escape through a crack in an UST over a long time period (a slow leak)? Answering this question provides information about the likely phase distribution and mobility of the contaminant and some idea of the extent of weathering. A slow leak that began long ago is likely to have spread farther and undergone considerably more weathering than a quick release. There is also likely to be less free product in a slow leak than in a quick spill (assuming equal spill volumes).

GATHERING SITE-SPECIFIC INFORMATION

Site-specific information pertains to the hydrologic and geologic characteristics of the site. Historic hydrologic data is typically available through state or local climatology offices or through the local USGS office. These records can provide a reliable and accurate source of typical rainfall patterns in the region. Geologic characteristics on the other hand vary greatly, even over short horizontal or vertical distances. Most states have extensive resources which show typical regional geologic features and conditions. Accurately estimating soil parameters at an individual site is difficult. Regional geologic data, such as can be found at the local USGS office, can be used to estimate the type(s) of soil formation likely to underlie a given site.

A great deal of useful information pertaining to the site is likely to have already been compiled and available through a variety of sources. A review of these data can prove invaluable to a preliminary assessment. The following list can help the user collect site-specific data:

- Local public works departments or similar agencies can provide plans of roadways, water pipelines, and sanitary and storm sewers. These drawings may contain boring logs that can help characterize site stratigraphy. Department employees are usually knowledgeable about the types of materials likely to be encountered during excavation and depth of the local water table. They are also likely to have information on the location of groundwater wells and surface water bodies used for drinking water in the area.

- Utility companies should be advised of the project and usually can provide plans of gas or oil pipelines and power and telephone cables.

- State UST programs may have a variety of useful information.

- The USGS can provide topographic, geologic and hydrologic maps and data. Local sources of water supply may also be found at the USGS office along with pumping rates of groundwater wells.

- U.S. Department of Agriculture Soil Conservation Service (SCS) has extensive data bases related to the subsurface parameters. County extension offices are common and can provide maps showing the types of soil formations and various hydrogeologic parameters likely to be encountered at the site.

- State or local climatology offices can provide typical annual rainfall rates and actual rainfall records for the period since the release occurred.

- The U.S. Census Bureau has a variety of water use data available to the public.

- Engineering firms that designed or built nearby buildings may have drawings and other data useful in the assessment. Local surveyors may also be able to provide useful information.

- Ask questions! This is only a starting point for collecting historic data. The people you talk to may not have what you are looking for, but they might know where to get it.

Estimating the type of soil formation (geologic conditions) underlying a site is probably the single most difficult aspect of a site assessment. It is also a very important parameter because many other site-specific parameters are estimated based on the understanding of site geology. Therefore, spending a significant time to develop an understanding of site geology is justified.

Table 2 presents site-specific data useful in a site assessment. This table, in conjunction with others in this subsection, can be used to estimate many site-specific parameters. Included in Table 2 are: 1) site-specific parameters; 2) a default source for obtaining the data; and 3) the importance of the parameter in the assessment. The default source column has been provided to facilitate a quick, preliminary site assessment. Field measurements are indicated as the default source where the measurements are easily obtained or where estimates are inappropriate due to inadequate or highly variable data. For the remaining parameters, values can easily be found in tables and figures within the manual or through the sources listed above. An example of how to use Table 2 in conjunction with other tables and figures in the manual is presented later in this subsection.

Descriptions of the field measurements required in Table 2 are not provided in this manual. If a description of these or other field measurements is desired, there are many publications that discuss in detail how to conduct field tests and collect and analyze samples.

Table 3 lists values for physicochemical properties of various types of soils and rock. These properties are important in determining how liquids (both groundwater and bulk product) move through the subsurface. Table 4 shows typical soil grain sizes and unit surface area values for various soil types. Soil surface area per unit volume of soil can be used to estimate the degree to which contaminants become sorbed to soil particles. Soil grain size can be used to estimate the capillary forces

TABLE 2. SITE-SPECIFIC PARAMETERS

PARAMETER (UNITS)	DEFAULT SOURCE	IMPORTANT FOR DETERMINING:
Soil Porosity (%)	Table 3	Mobility, Phase
Particle Density (g/cm^3)	Table 3	Mobility, Phase
Bulk Density (g/cm^3)	Table 3	Mobility, Phase
Hydraulic Conductivity (cm/sec)	Table 3	Mobility, Phase
Permeability (cm^2)	Table 3	Mobility, Phase
Air Conductivity	Table 3	Mobility, Phase
Depth to Groundwater (m)	Field Measure or through Site or Local records	Phase
Groundwater Temperature (^{o}C)	Figure 4	Mobility, Phase
Soil pH	Measure	Bacterial Activity
Rainfall Infiltration Rate (cm/day)	Local precipitation and evaporation records	Mobility, Phase,
Soil Surface Area (m^2/g)	Table 4	Mobility, Phase
Organic Content of Soil (%)	Measure	Mobility, Phase

TABLE 3. PHYSICOCHEMICAL PROPERTIES OF ROCKS AND SOIL

Rock/Soil Type	Soil Porosity (%)	Particle Density (g/cm^3)	Bulk Density (g/cm^3)	Hydraulic Conductivity (cm/sec)	Permeability (cm^2)	Air Conductivity (cm/sec)
UNCONSOLIDATED						
Gravel	25-40	2.65	1.59-1.99	10^{-1} - 10^{2}	10^{-6} - 10^{-1}	10^{-2} - 10
Sand	25-50	2.65	1.33-1.99	10^{-4} - 10	10^{-9} - 10^{-5}	10^{-5} - 10^{-1}
Loam	42-50	2.65	1.33-1.54	10^{-5} - 10^{-1}	10^{-10} - 10^{-6}	10^{-6} - 10^{-2}
Silt	35-50	2.65	1.33-1.72	10^{-7} - 10^{-3}	10^{-12} - 10^{-8}	10^{-8} - 10^{-4}
Clay	40-70	2.25	0.68-1.35	10^{-10} - 10^{-7}	10^{-15} - 10^{-12}	10^{-11} - 10^{-8}
CONSOLIDATED						
Sandstone	5-30	2.65	1.86-2.52	10^{-8} - 10^{-4}	10^{-13} - 10^{-9}	10^{-9} - 10^{-5}
Shale	0-10	2.25	1.98-2.25	10^{-11} - 10^{-7}	10^{-16} - 10^{-12}	10^{-12} - 10^{-8}
Granite	0-5	2.70	2.57-2.70	10^{-11} - 10^{-8}	10^{-16} - 10^{-13}	10^{-12} - 10^{-9}
Granite (fractured)	0-10	2.70	2.43-2.70	10^{-6} - 10^{-2}	10^{-11} - 10^{-7}	10^{-7} - 10^{-3}
Limestone	0-20	2.87	2.30-2.87	10^{-7} - 10^{-4}	10^{-12} - 10^{-9}	10^{-8} - 10^{-5}
Limestone (Karstic)	5-50	2.71	1.36-2.57	10^{-4} - 1	10^{-9} - 10^{-5}	10^{-5} - 10^{-1}
Basalt (permeable)	5-50	2.96	1.48-2.81	10^{-5} - 1	10^{-10} - 10^{-5}	10^{-6} - 10^{-1}

---

* Air conductivity values at 10°C. Values are based on the ratio of hydraulic conductivity to air conductivity (K_r); where $K_r =$ (viscosity of air/viscosity of water) (density of water/density of air)

Source: Adapted from Freeze and Cherry, 1979, and Krishnayya et al, 1988.

TABLE 4. RELATIONSHIP BETWEEN DIAMETER OF PARTICLES AND SURFACE AREA

Diameter of Particles (mm)	Description	Approximate Surface Area (m^2/g)
1.0 - 2.0	Very Coarse Sand	0.001 - 0.003
0.5 - 1.0	Coarse Sand	0.003 - 0.005
0.25 - 0.5	Medium Sand	0.005 - 0.01
0.1 - 0.25	Fine Sand	0.01 - 0.03
0.05 - 0.1	Very Fine Sand	0.03 - 0.1
0.002 - 0.05	Silt	0.1 - 1
<0.002	Clay	>1

Source: Adapted from Hillel, 1980

likely to be exerted on groundwater or liquid contaminant. Figure 4 is a contour map of the United States showing typical groundwater temperatures. Groundwater temperature is useful in determining whether biorestoration will be effective at a site. An estimate of the groundwater temperature at a site of interest can be made by interpolating between the two contour lines on either side of the site location.

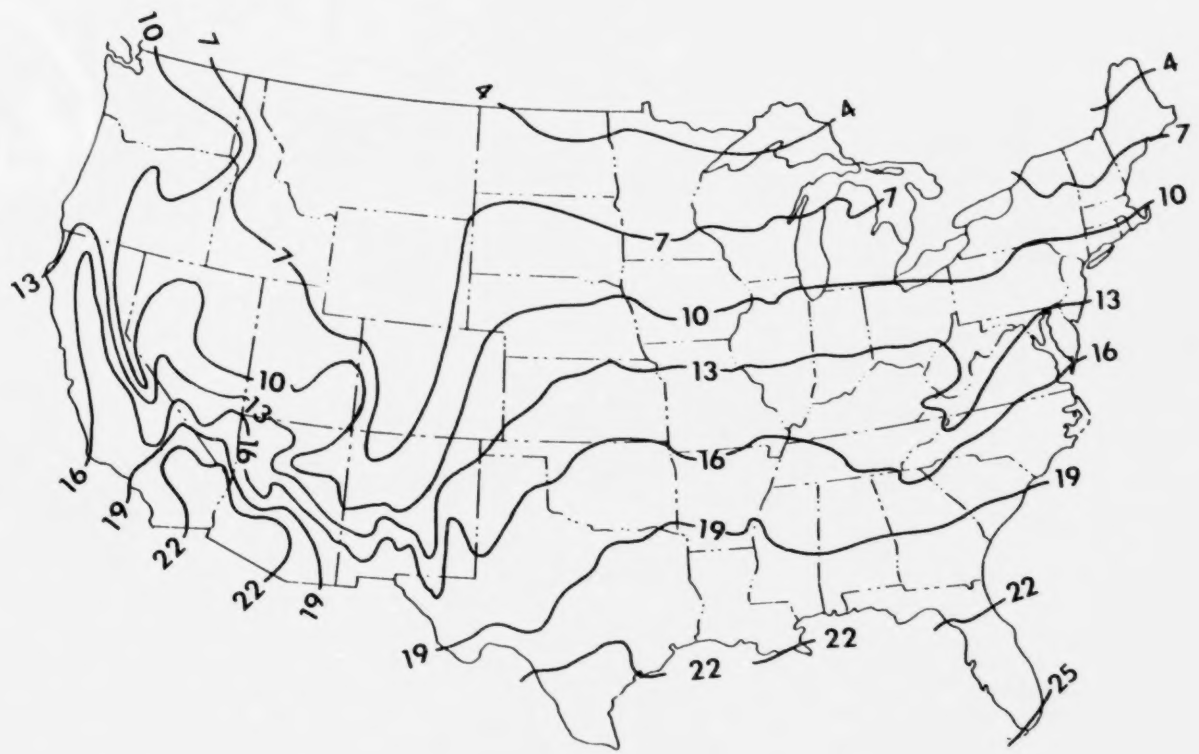
After geologic conditions have been estimated, Table 2, along with other tables and figures of this subsection, can be used to provide default values for some site-specific parameters. To illustrate, assume that the subsurface is found to be predominantly sand and gravel with several discontinuous clay layers or lenses at various intervals. If an estimate of the hydraulic conductivity at the site is needed two values will be required because the clay lenses are much less permeable and restrict groundwater movement relative to the sand and gravel. In Table 2, the user can locate the hydraulic conductivity parameter in the left-most column and identify Table 3 as the default source. Turning to Table 3, the user can locate values in the hydraulic conductivity column corresponding to sand, gravel and clay. Notice that the values are presented as ranges. With no other information, it is reasonable to assign values in the middle of the range. For clay, an assumed value of 10^{-8} cm/sec is reasonable. For a sand and gravel formation, a value of 10^{-1} cm/sec is near the middle of the two ranges and can serve as a preliminary estimate.

Other Important Site-Related Information - An important component of a good remediation plan is a prioritization of clean-up activities. To decide the best course of action at a site all exposure pathways (e.g. groundwater, vapors, etc.) must be identified. This will help those implementing a remediation plan address the most urgent aspects of remediation first. Figure 5 is a schematic diagram of a typical site where contamination of the saturated zone has occurred. The diagram includes possible receptors and shows some of the exposure pathways whereby contaminants could impact the receptors.

If done early in the remediation program, priority planning can save unnecessary effort. For example, if a groundwater supply were located 1,000 feet downgradient of the release site, a first priority would be to prevent the contaminant plume from reaching the supply. If this condition is not identified early in the assessment, containment of the contaminant plume might not be implemented quickly enough to prevent contamination of the supply. As shown in Figure 3, this manual can help the user plan and guide site activities. It identifies alternative technologies appropriate for a given activity (i.e., remediation goal) and helps the user select the best alternative.

Below are some of the factors which should be considered.

- Location of water resources - This includes surface water bodies (lakes, rivers and wetlands) and aquifers. It is important to note whether the resource is used for drinking water, but most water resources will fall under regulatory protection regardless of use. It is also important to note seasonal fluctuations in water levels, which influence regional groundwater flow. In the


4
4
4
4
7
7
7
7
7
10
10
10
10
10
13
13
13
13
13
16
16
16
16
16
19
19
19
19
19
19
22
22
22
22
22
22
25

(From Heath, 1983)

Figure 4. Groundwater Temperature in the United States (°C) at Depths of 10 to 25 M

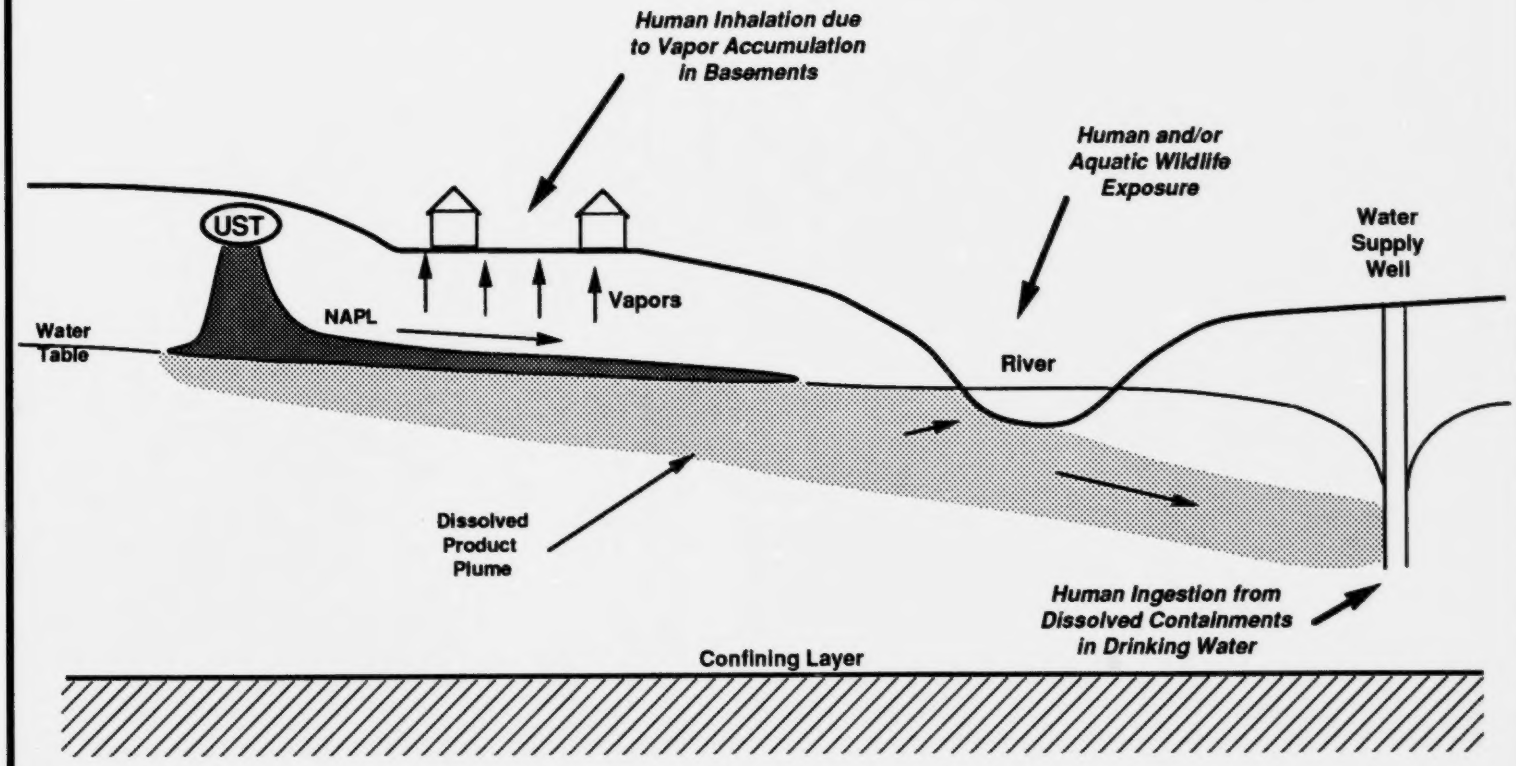

Human Inhalation due
to Vapor Accumulation
in Basements
Human and/or
Aquatic Wildlife
Exposure
UST
Water
Supply
Well
NAPL
Vapors
Water
Table
River
Dissolved
Product
Plume
Human Ingestion from
Dissolved Containments
in Drinking Water
Confining Layer

Figure 5. Potential Exposure Pathways Due to a Petroleum Product Release

dry summer months, groundwater may flow into a surface water body but during the spring, flow may be from the surface water to the groundwater. The pumping rates of all groundwater wells in the region should be determined, including seasonal changes in the pumping rate. Pumping wells alter local groundwater flow direction and may draw a contaminant plume when other data would suggest the plume would travel elsewhere. The pumping rates can also be used to determine capture zones within which groundwater will travel to the well, but this is usually time consuming and costly.

- Location of homes and buildings - Many petroleum products are very volatile and vapors from the contaminant plume can accumulate in the basements of homes and buildings. These vapors can be inhaled and can also pose an explosive threat.

- Location of underground utilities in the site area - Backfill materials used in utility trenches are often far more permeable than the surrounding natural formations. Contaminants may travel preferentially along these pathways, resulting in unexpected plume migration patterns. Utilities may also interfere with construction of some technologies.

- Clean-up criteria and disposal standards - Local or regional regulatory agencies should be contacted at the start of the site assessment. They often require that clean-up efforts continue until groundwater quality reaches state or federal legal requirements and that wastewater or solid waste disposal regulations are met. They will also likely want to be informed of remediation plans and kept abreast of clean-up progress. Knowing what the clean-up criteria are is important in technology selection because not all technologies are equally effective in removing contaminants.

GATHERING CONTAMINANT-SPECIFIC INFORMATION

Petroleum products are a mixture of many compounds. The physical and chemical properties of the constituents are different than those of the mixture, leading to the question of what to target during site assessment. In general, remediation efforts are usually tied to one or more individual constituents, but some aspects of the assessment warrant targeting the properties of the mixture.

Properties of individual constituents should be targeted:

- When the phase of contamination being evaluated is other than the original NAPL. For example, evaluation of the dissolved phase should focus on the more soluble constituents of the mixture since they are likely to comprise the greatest portion of dissolved contaminant mass. For most petroleum products, the BTEX compounds (benzene, toluene, ethylbenzene and xylene) comprise a significant portion of all dissolved constituents and can serve as the focus of dissolved contaminant evaluation.

- If the mixture has "weathered" considerably. Weathering is the process where a complex compound is reduced to its simpler component parts or biodegraded over time. If a petroleum product has been in the subsurface for several years, concentrations of certain contaminants will be significantly different than when originally released.

- To focus the assessment on a compound that is thought to present the greatest potential threat. For instance, it may be desirable to select a remedial technology that is likely to be effective in removing benzene, a known human carcinogen and common constituent of gasoline. An understanding of how benzene behaves in the subsurface would be developed rather than an understanding of the behavior of the mixture.

- To design a treatment system. The design of many technologies are based on theories and equations that are sensitive to the properties of the compound being treated. Specific compounds will generally be targeted based on their impact to the site.

Properties of the NAPL mixture should be targeted:

- When the phase of contamination being evaluated is the original NAPL.

- To evaluate the physical movement of NAPL through the subsurface.

Table 5 lists the contaminant properties useful in evaluating contamination in the saturated zone and can be used in a manner similar to Table 2. Included in Table 5 are: 1) contaminant-specific parameters useful in assessing a site; 2) default sources where parameter values can be located within the text; and 3) what each parameter is used for in the assessment. To facilitate a preliminary site assessment, listings of parameter values have been compiled from various literature sources. These can be used to estimate contaminant-specific parameter values.

Looking at Table 5, the user can identify from the default source column where in this manual literature values for each parameter may be found. To illustrate, assume an estimate of the liquid density of automotive gasoline is needed. The user can locate liquid density in Table 5 and find that the default source is Table 7. Moving to Table 7, the typical value for automotive gasoline in the liquid density column is 0.73 g/cm^3.

Table 6 presents the composition of three common hydrocarbon products in bulk. The table can be used to determine which constituents are likely to be in a given petroleum product and to estimate what percentage of the total product they represent.

Tables 7 and 8 list default values for various physical and chemical properties of common hydrocarbon mixtures and individual hydrocarbon constituents respectively. Table 7 would be consulted if the assessment targeted removal of the bulk product. For example, if removal of floating

TABLE 5. CONTAMINANT SPECIFIC PARAMETERS

PARAMETER (UNITS)	DEFAULT SOURCE	IMPORTANT FOR DETERMINING:
Vapor Pressure (mm Hg)	Tables 7, 8	Mobility, Phase
Water Solubility (mg/L)	Tables 7,8	Mobility, Phase
Liquid Viscosity (cP)	Tables 7, 8	Mobility
Liquid Density (g/cm^3)	Tables 7, 8	Mobility
Soil Sorption Coefficient (L/kg)	Table 8	Mobility, Phase
Refractory Index (ratio)	Table 9	Degradation
Unweathered Composition (-)*	Table 6	Mobility, Phase, Degradation

---

* Composition will change over time due to "weathering." See discussion in text.

TABLE 6. UNWEATHERED COMPOSITION OF THREE COMMON HYDROCARBON PRODUCTS

Hydrocarbon Group	Representative Hydrocarbon	Selected Representative Concentrations (%w/w) 1 Automotive Gasoline	2 #2 Fuel Oil	3 Jet Fuel JP-4
n-Alkanes		10.8 - 29.6		
C4	n-Butane	4.8 - 7.0		0.12
C5	n-Pentane	1.9 - 4.5		1.06
C6	n-Hexane	2.0 - 12.9		2.21
C7	n-Heptane	0.2 - 2.3		3.67
C8	n-Octane	1.3		3.80
C9	n-Nonane	0.4 - 0.8		2.25
C10-C14	n-Decane	0.2 - 0.8		8.73
Branched Alkanes		18.8 - 59.5		
C4	Isobutane	0.7 - 2.2		0.66
C5	Isopentane	8.6 - 17.3		
C6	2-Methylpentane	4.6 - 9.7		2.27
C7	2-Methylhexane	1.4 - 8.3		5.48
C8	2,4-Dimethylhexane	1.8 - 16.7		8.82
C9	2,2,4-Trimethylhexane	1.2 - 2.7		3.36
C10-C14	2,2,5,5-Tetramethylhexane	0.5 - 2.6		1.35
Cycloalkanes		3.2 - 13.7		
C5		0.2		
C6	Cyclohexane	1.0 - 3.9		2.40
C7	Methylcyclohexane	0.2 - 1.4		3.77
C8	1,2,4-Trimethylcyclopentane	0.2 - 0.7		1.35
Others	1,1,3-Trimethylcyclohexane	1.6 - 7.5		3.21
Olefins		5.5 - 13.5		
C4	1-Butene	0.9		
C5	1-Pentene	1.3 - 3.3		
C6	1-Hexene	0.8 - 1.8		
Others		2.5 - 7.5		
Mono-aromatics		19.3 - 40.9		
Benzene	Benzene	0.9 - 4.4		0.50
Toluene	Toluene	4.0 - 6.5		1.33
Xylenes	m-Xylene	5.6 - 8.8	0.07	2.32
Ethylbenzene	Ethylbenzene	1.2 - 1.4	0.03	0.37
C3-benzenes	1,3,5-Trimethylbenzene	3.2 - 11.3	0.67	3.59
C4-benzenes	1,4-Diethylbenzene	2.1 - 2.6	0.88	3.98
Others		1.6 - 5.2		

(Continued)

TABLE 6 (continued)

Hydrocarbon Group	Representative Hydrocarbon	1 Automotive Gasoline	2 #2 Fuel Oil	3 Jet Fuel JP-4
Phenols				
Phenol	Phenol		0.001	
C1-phenols	o-Cresol		0.01	
C2-phenols	2,4-Dimethylphenol		0.02	
C3-phenols	2,4,6-Trimethylphenol		0.02	
C4-phenols	m-Ethylphenol		0.01	
Indanol	Indanol		0.001	
Poly-aromatics	Fluorene		0.57	
Nitro-aromatics				
C1-Anilines			0.003	
C2-Anilines			0.004	
Complex Anilines	Quinoline		0.002	
Di-aromatics	Naphthalene	0.7	3.43	1.59
Saturated hydrocarbons				
C8	n-Octane		0.05	
C9	n-Nonane		0.20	
C10	n-Decane		0.58	
C11	n-Undecane		0.98	
C12	n-Dodecane		1.14	
C13	n-Tridecane		1.20	
C14	n-Tetradecane		1.31	
C15	n-Pentadecane		1.42	
C16	n-Hexadecane		1.53	
C17	n-Heptadecane		1.51	
C18	n-Octadecane		1.31	
C19	n-Nonadecane		1.16	
C20	n-Eicosane		0.99	
C21	n-Heneicosane		0.51	
C22	n-Docosane		0.29	
C23	n-Tricosane		0.15	
C24	n-Tetracosane		0.05	
Pristane			0.52	
Phytane			0.46	
Unknowns		6.6-13.8		

NOTE: Blanks indicate the unavailability of data and do not indicate the absence of a particular compound from the hydrocarbon product.

SOURCES:

Column 1: Hoag et al, 1984; EPA, 1984; Ghassemi et al, 1984.
Column 2: ICF, 1984
Column 3: Smith et al, 1981.

TABLE 7. PHYSICOCHEMICAL PROPERTIES OF FIVE COMMON HYDROCARBON MIXTURES

PRODUCT	LIQUID DENSITY (g/cm^3)	LIQUID VISCOSITY (cPoise)	WATER SOLUBILITY (mg/L)	VAPOR PRESSURE (mm Hg)
Automotive Gasoline	(0.73) 0.72-0.76 [15.6]	(0.45) 0.36-0.49 [15.6]	(158) 131-185 [13-25]	(469) 263-675 [38]
#2 Fuel Oil	(0.91) 0.87-0.95	(1.56) 1.15-1.97 [21]	3 - 10 [20 - 23]	(14.3) 2.12-26.4 [21]
#6 Fuel Oil	(0.91) 0.87-0.95	(254) 14.5-493.5 [38]	~5	(14.3) 2.12-26.4 [21]
Jet Fuel (JP-4)	0.75	0.829 [21]	10 - 20	91
Mineral Base Crankcase Oil	0.84-0.96 [15]	275 [38]	insoluble	N/A
Air	----------	---------	------	760
Saturated Aqueous Vapor	1	1	------	17.5

N/A = Not Available

Notes: All values for 20°C unless noted in brackets [ ].
Values in parentheses are typical of the parameter ( ).
Values for air and saturated aqueous vapor are included, where applicable, as a means of comparison.

Source: Compiled from various published and unpublished sources.

Table 8 . Chemical Properties of Hydrocarbon Constituents

Chemical Class	Representative Chemical	Liquid Density ($g/cm.^3$) @ 20°C	Liquid viscosity (cPoise) @ 20°C	Water solubility (mg/L) @ 25°C	Pure Vapor Pressure (mm Hg) @ 20°C	Soil Sorption Constant (Koc) (L/kg) @ 25°C
n-Alkanes						
C4	n-Butane	0.579	0.177	61.1	1560	250
C5	n-Pentane	0.626	0.224	41.2	424	320
C6	n-Hexane	0.659	0.306	12.5	121	600
C7	n-Heptane	0.684	0.409	2.68	35.6	1300
C8	n-Octane	0.703	0.542	0.66	10.5	2600
C9	n-Nonane	0.718	0.620	0.122	3.2	5800
C10	n-Decane	0.730	0.740	0.022	0.95	13000
Mono aromatics						
C6	Benzene	0.885	0.638	1780	75.2	38
C7	Toluene	0.867	0.580	537	21.8	90
C8	m-Xylene	0.864	0.608	162	6.16	220
C8	Ethylbenzene	0.867	0.666	167	7.08	210
C9	1,3,5-Trimethylbenzene	0.865	0.727	72.6	1.73	390
C10	1,4-Diethylbenzene	0.862	0.700	15	0.697	1100
Phenols						
Phenol	Phenol	1.058	12.7	438	0.529	110
C1-phenols	m-Cresol	1.027	20.8	26175	0.15	8.4
C2-phenols	2,4-Dimethylphenol	0.965	NA	NA	0.058	NA
C3-phenols	2,4,6-Trimethylphenol	NA	NA	NA	0.012	NA
C4-phenols	m-Ethylphenol	1.037	NA	NA	0.08	NA
Indanol	Indanol	NA	NA	NA	0.014	NA
Di-aromatics	Naphthalene	1.025	NA	31.7	0.053	690

NOTE: NA - Not availabe
SOURCE: Compiled from various published and unpublished sources.

NAPL is being considered, the mobility of the floating NAPL plume would be evaluated using the properties of the bulk liquid.

Table 8 would be used for individual constituents. For example, if the user wished to evaluate the effectiveness of various technologies at removing or treating dissolved contaminants, the more soluble components of the bulk liquid, such as the BTEX compounds, would be targeted. It should be noted that the contaminant-specific properties of petroleum product constituents in Table 8 are for pure compounds. These values may be different than would be found when a given compound is mixed with other organic compounds. For example, the water solubility of pure benzene is 1,780 mg/L, but in a gasoline/water mixture the dissolution of benzene is more likely to be in the 20 to 80 mg/L range.

Table 9 lists selected refractory index values for both hydrocarbon mixtures and individual constituents. The refractory index is a measure of the relative biodegradability of a compound. It is useful in evaluating the likely effectiveness of biodegradation as a treatment technology and can also be used to help determine the impact of weathering on a very old release. For example, if a release occurred many years ago, natural biodegradation has likely occurred. Less biodegradable compounds such as xylene or ethylbenzene are more likely to persist in the groundwater than the more degradable benzene. Values for some bulk product mixtures, such as gasoline and kerosene, as well as common hydrocarbon constituents are presented.

EVALUATING CONTAMINANT PHASES IN THE SATURATED ZONE

Petroleum products reaching the saturated zone will primarily be found in one of three phases: 1) non-aqueous phase liquid (NAPL); 2) dissolved in groundwater; and 3) sorbed to soil particles. Initially, for relatively large releases, almost all of the petroleum product will exist as NAPL, but over time, a portion of the NAPL will transfer to the dissolved and sorbed phases. If the release is relatively small, all the NAPL may be trapped in the unsaturated zone as residual liquid and dissolved product will be the only contaminants reaching the saturated zone (via infiltrating rainwater).

Estimating how much contaminant is in each of the three phases is important in staging an effective remediation of the saturated zone. If most of the contaminant is in the dissolved phase and/or if dissolved contaminant is considered most likely to impact local receptors, remediation efforts should recognize this. For a large, recent release, most of the contaminant that reaches the water table likely remains as bulk product on the water table and a remediation plan should likely be focused towards NAPL recovery. In either case, the user could refer to Figure 3 to identify technologies that are appropriate for a given condition.

Background

Quantitative estimates of the mass or volume of contaminant in any one of the three phases requires field sampling and analysis. An overview of commonly used procedures and some of the problems encountered in

TABLE 9. REFRACTORY INDEX FOR COMMON HYDROCARBONS

COMPOUND	RATIO
RELATIVELY UNDEGRADABLE	
Butane	≃0
Ethane	≃0
Heptane	≃0
Hexane	≃0
Isobutane	≃0
o-Xylene	<0.008
m-Xylene	<0.008
Ethylbenzene	<0.009
MODERATELY DEGRADABLE	
Gas oil (cracked)	~0.02
Gasolines (various)	~0.02
Mineral spirits	~0.02
Nananol	>0.033
Undecanol	<0.04
1-Hexene	<0.044
Dodecanol	0.097
RELATIVELY DEGRADABLE	
p-Xylene	<0.11
Toluene	<0.12
Jet fuels (various)	≃0.15
Kerosene	~0.15
Range oil	≃0.15
Naphthalene	<0.20
Hexanol	≃0.20
Octanol	0.37
Benzene	<0.39
Phenol	0.81

---

*The refractory index is the ratio of BOD5 to COD

Source: Adapted from Lyman *et al*, 1982 estimating the amount of contaminant in each phase is presented below. This is followed by worksheets that can help the user qualitatively estimate phase partitioning with a minimum of field data.

Volume of Floating NAPL

Volume determinations of floating hydrocarbons are typically obtained by the following equation:

$$V_N = A_N T_N n \qquad (1)$$

where: A_N = areal extent of the NAPL plume;
T_N = average thickness of the NAPL plume; and
n = effective porosity of the soil formation.

Several methods for determining areal extent of the plume are described in the contaminant mobility subsection immediately following this subsection.

The effective porosity of the soil formation reflects the actual volume available (of the total pore volume) that can be occupied by NAPL. Since some water will be retained in the pore spaces as residual saturation, the volume available for NAPL will be less than the total pore volume reflected in porosity values.

NAPL thickness is fairly difficult to estimate accurately because the apparent thickness of the plume, as measured in a monitoring well, is typically greater than the true thickness. NAPL thickness will also vary throughout the plume, particularly if pumping wells are installed to contain the plume. Measuring plume thickness at several locations allows a better estimate of the average thickness.

Figure 6 is a schematic diagram of a typical monitoring well within a free floating contaminant plume. The apparent thickness is generally greater than the true thickness because the actual free product plume outside the well floats on the capillary zone above the water table rather than on the water table itself. Capillary forces within the well are virtually non-existent and the product within the well floats on the water table. Additional free product will flow into the well due to the gradient difference between product in the well and product in the adjacent formation. As additional product migrates to the well, the weight of the column of bulk product in the well tends to depress the water level in the well below that outside the well, increasing the difference between apparent and true thickness.

Among the factors that influence the ratio of apparent to true free product thickness are the capillary forces of the soil formation, interfacial tension forces (ITFs), and the volume of product released. Fine-grained materials such as clay or silt will have thicker capillary zones and greater apparent to true thickness ratios than coarse materials. If the ITFs between the contaminant and the soil particles are great, less product is likely to migrate to the well, decreasing the ratio. The ratio is also generally greater for smaller releases than for larger releases,

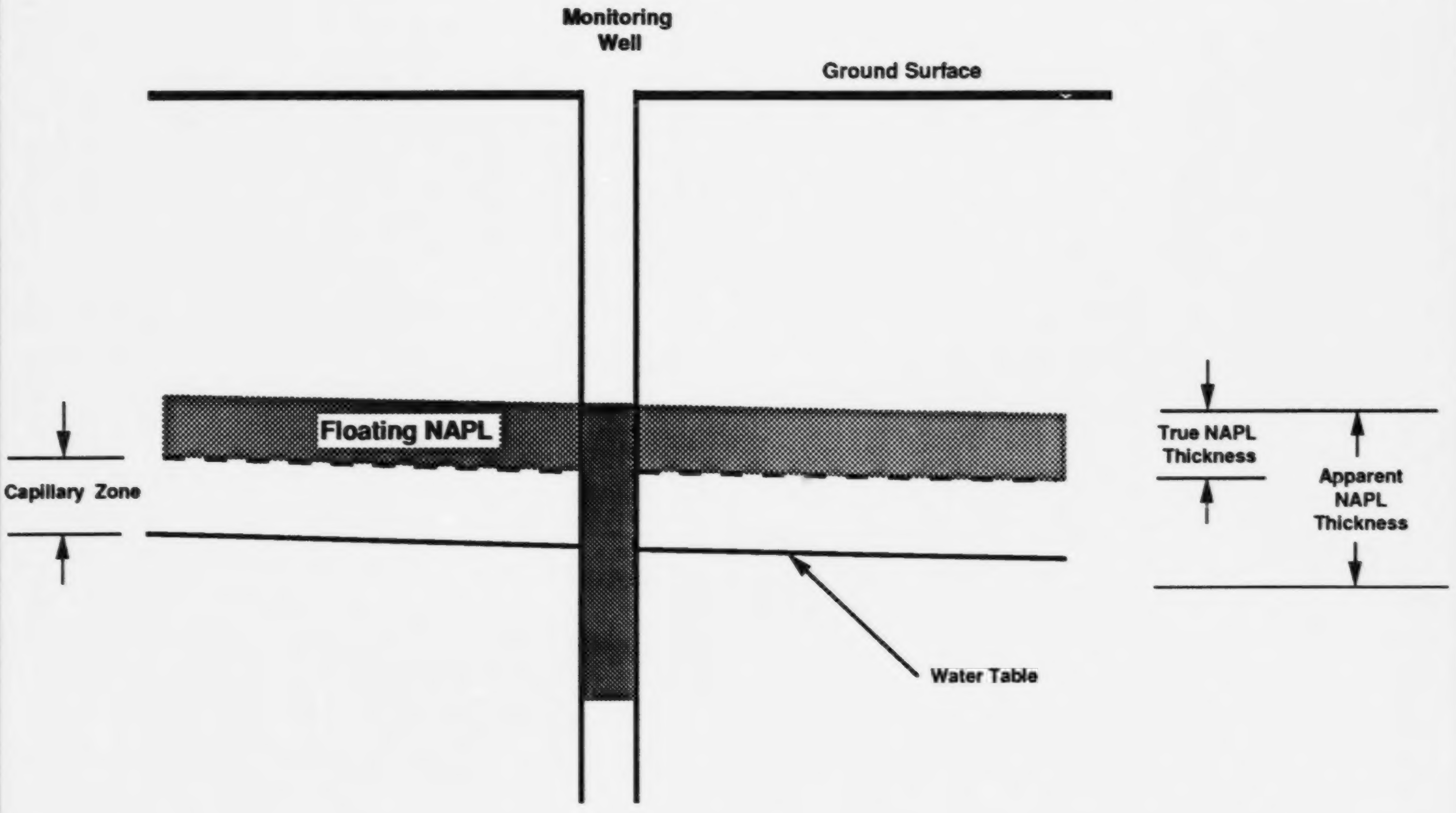

Monitoring
Well
Ground Surface
Floating NAPL
Capillary Zone
Water Table
True NAPL
Thickness
Apparent
NAPL
Thickness

Figure 6. Apparent Versus True Floating NAPL Thickness in a Groundwater Monitoring Well

because the capillary fringe is compressed more for large releases. The apparent to true thickness ratio in clay can be as high as 10:1 while for a coarse gravel this ratio may approach 1:1.

Figure 7 provides rough estimates of typical apparent to true NAPL thickness ratios for various soil types. The equations used to develop the figure assume a uniform pore size in the formation (Farr et al., 1990). Most soils do not have uniform pore sizes, particularly the silts and clays to the right side of the figure. However, these ratios provide a reasonable estimate for a preliminary assessment. The shaded portion of the figure represents possible ratios for a given soil type over the range of typical porosity and residual saturation values for the soil. The curve in the middle of the shaded area is the average ratio.

Several authors have proposed other methods to estimate free product thickness. An empirical method (Hall et al., 1984) relates true to apparent thickness with a formation factor. The formation factor varies with pore size and hydrocarbon surface tension. Bail-down testing is a widely used field method to evaluate the true thickness of petroleum hydrocarbon product in a monitoring well (Testa and Paczkowski, 1989). These sources, among others, can be consulted to estimate true thickness of the NAPL plume.

Mass of Dissolved and Sorbed Contaminants in Groundwater

To quantitatively estimate the mass of dissolved contaminants, the dissolved plume volume and average concentration must be known. This requires numerous samples from wells throughout the plume, both horizontally and vertically. The accuracy of such an estimate will depend on how well the horizontal and vertical extent of plume have been delineated (plume volume) and how well the collected groundwater samples characterize the plume (average concentration).

Contaminants are primarily introduced to groundwater as dissolved product where they migrate through the subsurface with the groundwater. In the subsurface, some fraction of the contaminants in solution will become attached or sorb to the surrounding soil particles. This partitioning removes a portion of the solute from solution, thus decreasing the concentration and total amount of compound available for transport further along the flow path (Sutton and Barker, 1985). Sorption of dissolved contaminants slows the center of mass of the plume relative to groundwater movement. This does not mean that the dissolved contaminant velocity is less than that of groundwater. Rather, the dissolved concentrations at the front of the plume are lessened due to adsorption, causing the plume center of mass to move slower than groundwater flow.

Thurman (1985) found that the degree of partitioning between the dissolved and sorbed phases depends primarily upon the percent organic content on the fine sediments, the amount of fine sediments and the water solubility of the organic solute. The greater the concentration of solute the more contaminant will be adsorbed. The organic content of the formation is important in sorption, but most groundwaters have relatively low organic content, typically less than 0.1 percent. Sutton and Barker (1985) found that the center of mass of four different contaminant plumes were not significantly retarded in a formation with low organic content

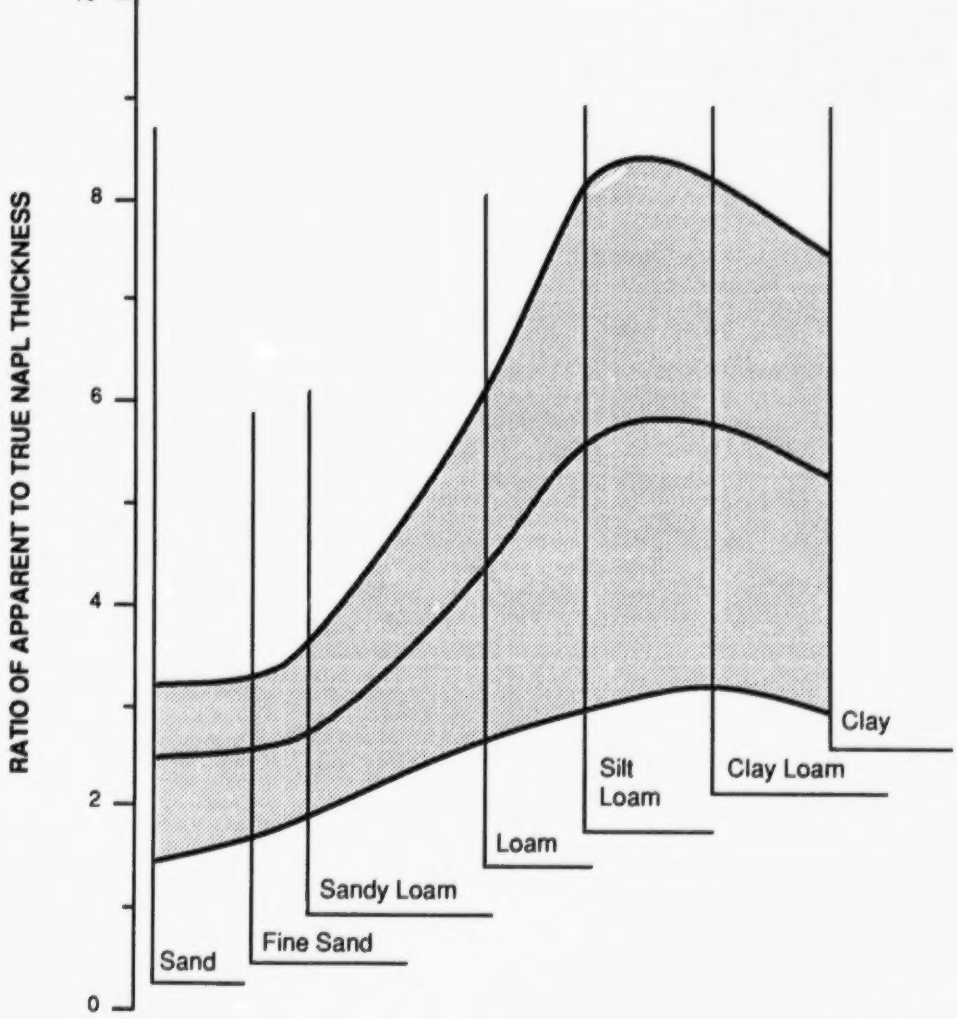


Figure 7. Ratio of Apparent to True NAPL Thickness for Various Soil Types

(less than 0.1 percent). Schwarzenbach and Westall (1981) noted that only soils less than 0.125 mm in diameter were important in sorption of organic solutes. This would limit most sorption processes in groundwater aquifers to silts, clays, and fine sands.

One method of estimating contaminant partitioning in the saturated zone is based on a retardation equation. The retardation factor (R) is the ratio of average linear velocity of groundwater to the velocity of the center of mass of the plume and is defined by the following equation:

$$R = 1 + (p_B/n)k_d \qquad (2)$$

where:
p_B = bulk density of the soil;
n = soil porosity; and
k_d = distribution coefficient.

The retardation factor can be used to relate the amount of contaminant in the dissolved phase to the amount in the sorbed phase. Bulk density and porosity are soil properties that can be found in Table 3. The distribution coefficient (k_d) is the ratio of mass of sorbed contaminant per unit mass of soil to concentration of dissolved contaminant and varies for a given compound. Literature values of k_d for various compounds can also be found in various sources.

The mass of dissolved contaminants (M_d) present in the saturated zone can be expressed as:

$$M_d = C\,n\,V \qquad (3)$$

where:
C = the average concentration of dissolved contaminant;
n = soil porosity; and
V = the volume of the dissolved plume.

The mass of sorbed contaminant (M_s) can then be estimated in the following way:

$$M_s = (R-1)\,M_d \qquad (4)$$

where: R = retardation factor.

Estimate of Partitioning

It is possible to approximate the phase partitioning in the saturated zone using Tables 10 and 11. These tables present some of the important factors to consider in evaluating phase partitioning. They also provide a way to estimate the likelihood of contamination being present in various phases by identifying the range of values over which conditions will favor one or another of the phases. For example, depth to groundwater plays an important role in determining how much NAPL reaches the water table. Table

Table 10. Likelihood of NAPL Being Present on the Water Table

FACTOR	UNITS	SITE OF INTEREST ▼	INCREASING LIKELIHOOD →		
RELEASE- RELATED					
* **• Amount Released**	gal		Small (<1,000) ○	Medium (1000-10,000) ○	Large (>10,000) ○
* **• Rate Of Release**	-		Slow Release ○	- - ○	Instantaneous Release ○
• Time Since Release	months		Long (>12) ○	Medium (1-12) ○	Short (< 1) ○
SITE - RELATED					
* **• Preferential Flow Pathways**	-		Not Present ○	Unknown ○	Present ○
* **• Depth To Groundwater**	meters		Deep (>15) ○	Medium (2-15) ○	Shallow (< 2) ○
• Hydraulic Conductivity (of the Unsaturated Zone)	cm/sec		Low ($<10^{-5}$) ○	Medium (10^{-5}-10^{-3}) ○	High ($>10^{-3}$) ○
• Rainfall Infiltration Rate	cm/day		High (0.2) ○	Medium (0.05-0.2) ○	Low (<0.05) ○
• Soil Temperature	°C		Cool (<10) ○	Medium (10 - 20) ○	Warm (>20) ○
• Soil Sorption Capacity (Surface Area)	cm^2/g		High (>1) ○	Medium (0.1-1) ○	Low (<0.1) ○
CONTAMINANT- RELATED					
* **• Liquid Viscosity**	cP		High (>20) ○	Medium (2-20) ○	Low (<2) ○
• Vapor Pressure	mm Hg		High (>100) ○	Medium (10-100) ○	Low (<10) ○
• Water Solubility	mg/L		High (>1000) ○	Medium (100-1000) ○	Low (<100) ○

* CSFs denoted with an asterisk are typically more important than other CSFs

Table 11. Likelihood of Dissolved Contaminants Being Present in the Saturated Zone

FACTOR	UNITS	SITE OF INTEREST ▼	INCREASING LIKELIHOOD →		
RELEASE- RELATED					
* • Amount Released	gal		Small (100) ○	Medium (100-1000) ○	Large (>1000) ○
* • Rate Of Release	-		Instantaneous Release ○	- -	Slow Release ○
* • Time Since Release	months		Short (<1) ○	Medium (1-12) ○	Long (>12) ○
SITE - RELATED					
• Depth To Groundwater	meters		Deep (>15) ○	Medium (2-15) ○	Shallow (<2) ○
• Fluctuating Water Table	-		Steady ○	Moderately Fluctuating ○	Highly Fluctuating ○
• Hydraulic Conductivity (of the Unsaturated Zone)	cm/sec		Low ($<10^{-5}$) ○	Medium (10^{-5}-10^{-3}) ○	High ($>10^{-3}$) ○
* • Rainfall Infiltration Rate	cm/day		Low (<0.05) ○	Medium (0.05-0.2) ○	High (>0.2) ○
• Soil Temperature	°C		Cool (<10) ○	Medium (10-20) ○	Warm (>20) ○
• Soil Sorption Capacity (Surface Area)	m^2/g		High (>1) ○	Medium (0.1-1) ○	Low (>0.1) ○
CONTAMINANT- RELATED					
• Liquid Viscosity	cP		High (>20) ○	Medium (2-20) ○	Low (<2) ○
• Vapor Pressure	mm Hg		High (>100) ○	Medium (10-100) ○	Low (<10) ○
*• Water Solubility	mg/L		Low (<100) ○	Medium (100-1000) ○	High (>1000) ○

* CSFs denoted with an asterisk are typically more important than other CSFs

11 shows that the likelihood of NAPL reaching the water table is significantly greater if depth to groundwater is less than 2 meters than if it is greater than 15 meters. The factors are categorized as release-related, site-related, and contaminant-related. Examples are provided in the Appendix of this manual that demonstrate how the worksheets can be used.

The factors of Tables 10 and 11 are not weighted to reflect their relative importance, but some do play a greater role than others in determining phase distribution. However, because the relative importance of the factors will vary from site to site, it is impossible to design an absolute ranking scheme for the factors. To help address this issue, the importance of each of the factors is discussed below, followed by a brief discussion of the relative importance of the factors.

Release Information

The amount and rate of release will affect the probability of all three phases being found in the saturated zone. Some releases are quick spills with high rates of release while others are leaks where small amounts of product are released over a period of time. Hydrocarbons will persist as bulk liquid longer for larger releases than for smaller releases, raising the likelihood of NAPL reaching the water table for large release incidents. Also, the greater the amount of NAPL reaching the saturated zone, the greater the amount of dissolved and sorbed contaminant there will be. A slow rate of release results in conditions more suitable to transfer from NAPL to other phases. Less NAPL is likely for a slow leak than for a quick spill given that the same total amount of product was released.

The time since the release may also be important. More recent releases of petroleum would more likely result in a higher proportion of NAPL relative to dissolved contaminants being present in the saturated zone. The dissolved and sorbed phases contain incrementally more of the contaminant mass for older releases because there is more opportunity for contaminants to dissolve in groundwater and sorb to soil particles over time.

Site-Related Information

The depth to groundwater and the soil sorption capacity (or surface area) of the unsaturated zone soils influence how much of the total release reaches the water table. The greater the depth to groundwater and the more surface area available for adsorption, the more likely contaminants will attenuate in the unsaturated zone before reaching the water table. This will result in less total contaminant in all three phases in the saturated zone. The surface area of soils below the water table plays an important role in partitioning between the dissolved and sorbed phases. Clays and silts, which have a relatively large surface area, will retain more contaminants in the sorbed phase than sands and gravels.

The relative ease with which contaminants can move down through the unsaturated zone to the water table is related to the hydraulic conductivity of soils above the water table and the existence of preferential flow pathways in the soils. Sands and gravels with high hydraulic conductivities allow more rapid transport of NAPL downward through the unsaturated zone. Preferential flow pathways are fractures, fissures or other openings in the soil, both natural and man-made, which allow more rapid movement of liquids than would normally be expected. Some examples are tree roots, well casings, and fractures due to shrinking and swelling of certain types of clay.

As rainfall infiltrates the unsaturated zone, the soluble components of the residual NAPL will dissolve and migrate towards the saturated zone. Therefore, the greater the rainfall infiltration rate, the greater will be the percentage of dissolved contaminants. If the release was fairly recent, actual rainfall records since the release provide better data than annual averages.

A fluctuating water table will cause increased transfer from NAPL to the dissolved phase. As the water table falls, the floating NAPL plume also falls. When the water table rises again, some NAPL gets trapped between the soil particles. A greater contact area between NAPL and groundwater is created and dissolution is increased.

Temperature affects partitioning of petroleum products in the subsurface primarily because of its effect on other parameters. As temperature increases; viscosity decreases, vapor pressure increases and water solubility increases. Warmer temperatures would likely result in increased amounts of NAPL and dissolved product in the saturated zone.

Contaminant-Related Parameters

A contaminant's water solubility is a measure of how easily it will dissolve in water. As solubility increases, more of the contaminant is likely to transfer from NAPL to the dissolved phase. Solubility is also temperature dependent; warmer groundwater will usually have more dissolved contaminant than cooler groundwater. Once in the dissolved phase, compounds with lower solubilities are more likely to sorb to soil particles below the water table than more soluble compounds.

A low liquid viscosity material, such as gasoline, will move more easily down through the unsaturated zone than a more viscous fuel oil. Therefore, lower viscosity suggests a greater likelihood of petroleum products reaching the saturated zone.

The vapor pressure of a material indicates the relative degree to which it will transform from the liquid or dissolved phase to the vapor phase. As vapor pressure increases, more of the contaminant is likely to be in the vapor phase, and therefore, less is likely to reach the saturated zone.

Relative Importance of Factors

The extent to which contaminants reach the saturated zone as NAPL plays a large role in the overall phase distribution of the contaminant in the saturated zone. If large amounts of NAPL reach the water table, then large amounts of dissolved and sorbed contaminants can also be expected. Therefore, factors that are important in evaluating NAPL are also important in evaluating other phases. The most important factors for each phase are discussed below.

NAPL - The amount released is probably the most important factor. If the amount released is very large, a significant amount of NAPL is likely to reach the water table regardless of other factors. For smaller releases, the rate of release, depth to groundwater, presence of preferential flow pathways and liquid viscosity play a larger role than other factors.

Dissolved Phase - As stated above, the factors that play an important role in estimating the presence of NAPL in the saturated zone are also important in determining the total mass of dissolved contaminant. For large releases, where significant amounts of NAPL reach the water table, the water solubility of the contaminant is probably most important. For small releases, the rainfall infiltration rate and soil porosity play increasingly important roles.

Sorbed - In the saturated zone, the amount of sorbed contaminant is closely related to the amount of dissolved contaminant. For a given contaminant and a given soil formation, the percentage of dissolved phase contamination that becomes sorbed to soil particles is roughly constant and can be significant. It is not uncommon for more than one-half of all contaminants below the water table to be in the sorbed phase. The most important factors in estimating the ratio of dissolved to sorbed contaminants are the water solubility of the contaminant and the type of soil.

EVALUATING CONTAMINANT MOBILITY

Implementing an effective remedial technology for the saturated zone requires an understanding of how far the contaminants have traveled (vertically as well as horizontally) and the direction and velocity of plume movement. Delineating the extent of contamination is an essential part of designing a containment system and also reveals what receptors may already be affected. Plume flow direction and velocity can also be used to predict what receptors are likely to be impacted and when the contaminant plume would reach the receptor if containment is not implemented.

The liquid and dissolved contaminant phases are highly mobile while sorbed contaminants are relatively immobile. The focus of this subsection is on the two mobile contaminant phases.

Extent of Contaminant Plume

Delineating the contaminant plume aids in locating monitoring and recovery wells and in assessing the impact to nearby receptors. Since the NAPL and dissolved contaminant can move at different rates and in different directions in the subsurface, the two phases may need to be delineated separately. Delineation of the down-gradient and lateral extent of the plume is generally more important than of the up-gradient extent because movement in the up-gradient direction is generally limited. However, the presence of pumping wells or surface waters up-gradient of the release should be noted. Seasonal changes in surface water elevations or changes in pumping rates can cause changes in local groundwater flow directions.

Monitoring wells, soil gas sampling, ground penetrating radar and resistivity surveys are among the techniques that can be used to determine the areal extent of contamination in the saturated zone. Use of monitoring wells is an accurate but expensive way to determine the extent of contamination. Other methods are less accurate but are often used as a preliminary means of delineating and determining where to best locate monitoring wells. Soil gas sampling is relatively inexpensive, can be done quickly and is probably the most commonly used of these methods.

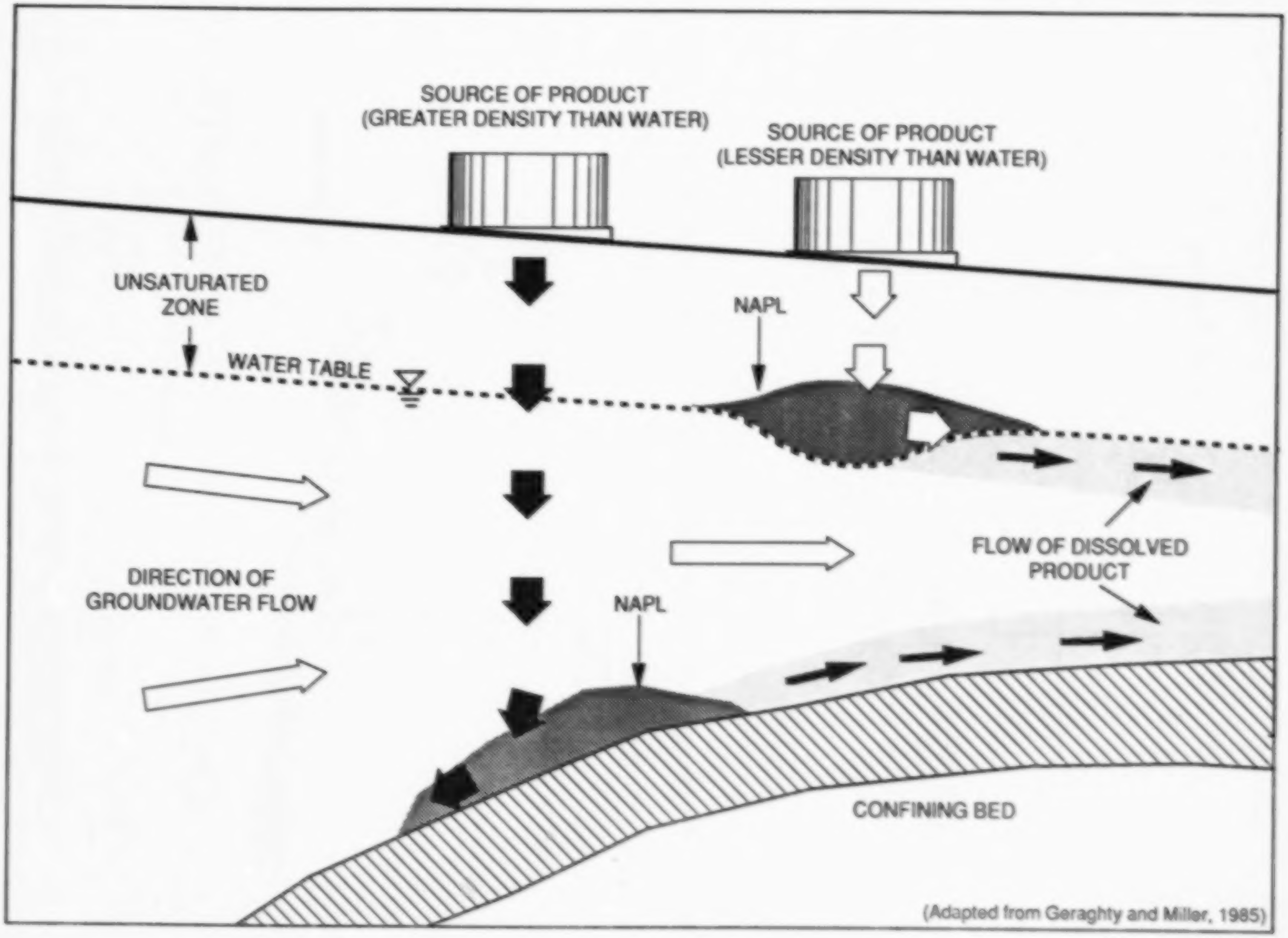
Most petroleum products are less dense than water and will float on the water table in the bulk liquid phase. However, if denser than water, the contaminant will sink through the aquifer until it reaches an impermeable barrier. The areal extent of a denser than water contaminant plume is more difficult to estimate. Floating product will move in the same general direction as groundwater, but movement of dense contaminants at the bottom of the aquifer is controlled by the grade of the impermeable barrier and may be different than groundwater movement. Figure 8 shows how the effects of density can influence contaminant migration. Notice that the flow direction of the denser than water bulk liquid is opposite that of the groundwater, but the dissolved component travels with the groundwater. Estimation of the areal extent of denser than water petroleum products is likely to require monitoring wells, especially if the saturated thickness of the aquifer is great.

The vertical extent of dissolved contaminant is important for several reasons:

- to calculate the volume of contaminant in the dissolved phase;
- to determine the depth of screening for monitoring wells; and
- to determine pumping rates required in recovery or containment wells.

If all the monitoring wells at a site are screened at or near the water table, they might not intercept a dissolved plume flowing deeper in the aquifer. Also, the entire dissolved plume may not be contained if the pumping rate is not adequate or recovery wells are not installed deep enough. A dissolved plume may exist relatively deep in the aquifer if the vertical component of groundwater flow is large. This is most prevalent at sites where the water table is relatively flat and the recharge rate is high. Infiltrating rain water acts to "push" the plume down below the water table. Figure 9 shows some of the ways poorly planned well installation can hinder the effectiveness of a remediation system.

An accurate estimate of the vertical extent of contamination is very difficult to make without monitoring wells, but a reasonably accurate preliminary estimate is possible before wells are installed. The most important factor in estimating vertical depth is contaminant density. For contaminants lighter than water, the dissolved product will likely be nearer the water table. Dense contaminants migrate to the bottom of the aquifer. If dissolved constituents are similar in density to water, they will likely be found dispersed throughout the aquifer. The time since the release can also influence the vertical location, because some natural


SOURCE OF PRODUCT
(GREATER DENSITY THAN WATER)
SOURCE OF PRODUCT
(LESSER DENSITY THAN WATER)
UNSATURATED
ZONE
NAPL
WATER TABLE
DIRECTION OF
GROUNDWATER FLOW
FLOW OF DISSOLVED
PRODUCT
NAPL
CONFINING BED

(Adapted from Geraghty and Miller, 1985)

Figure 8. The Effect of Density on Contaminant Plume Migration

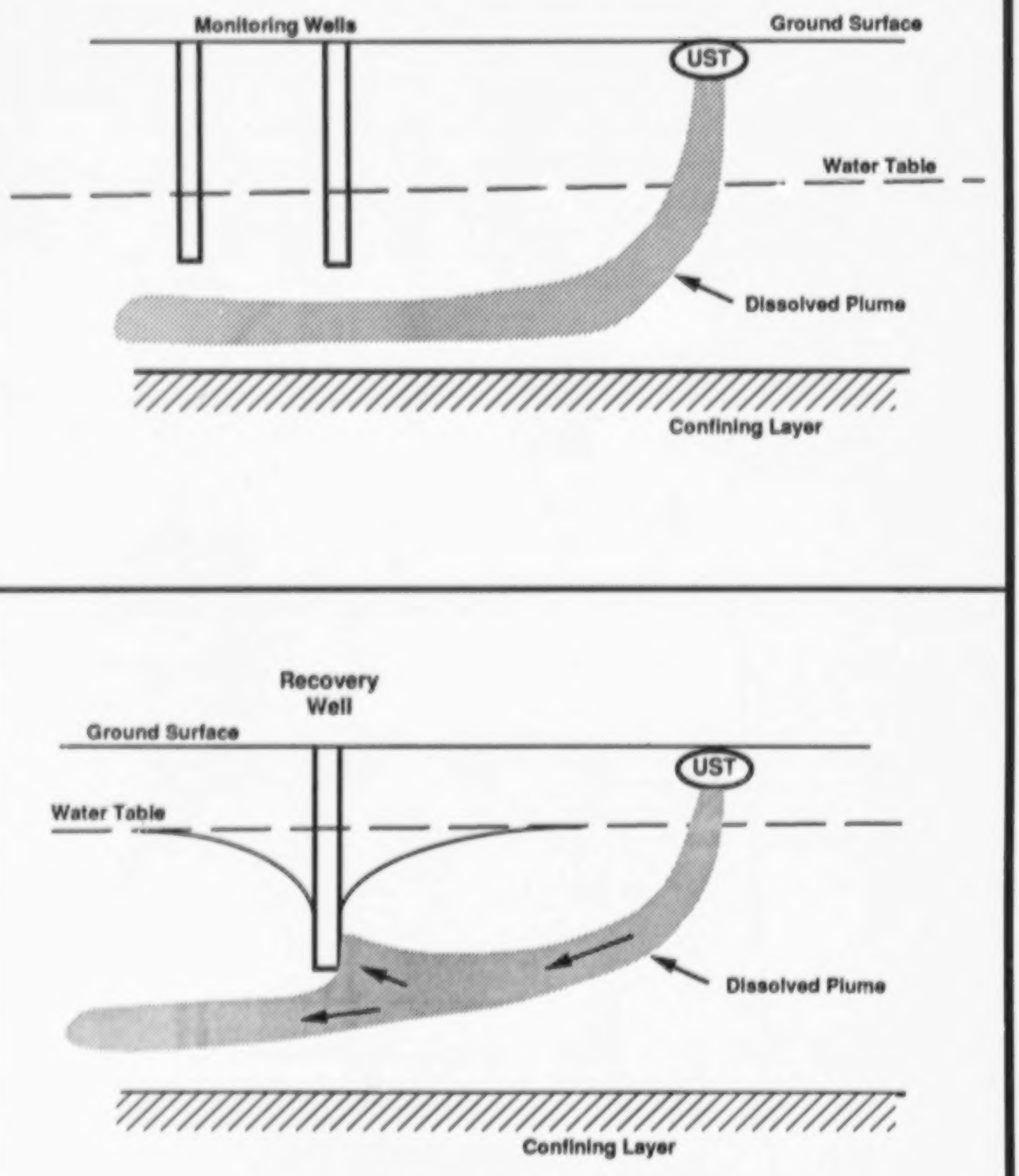

Monitoring Wells
Ground Surface
UST
Water Table
Dissolved Plume
Confining Layer
Recovery Well
Ground Surface
UST
Water Table
Dissolved Plume
Confining Layer

Figure 9. Poorly Designed Monitoring and Recovery Wells

dispersion of the dissolved plume will occur over time. For a very recent release of lighter than water contaminant, any dissolved product is likely to be close to the water table. As the dissolved product flows with the groundwater, dispersion forces will cause some of the contaminants to move lower in the aquifer. Another factor is site stratigraphy. Low permeability layers (aquitards) below the water table may effectively prevent vertical dispersion of dissolved contaminants.

Mobility of Contamination in the Saturated Zone

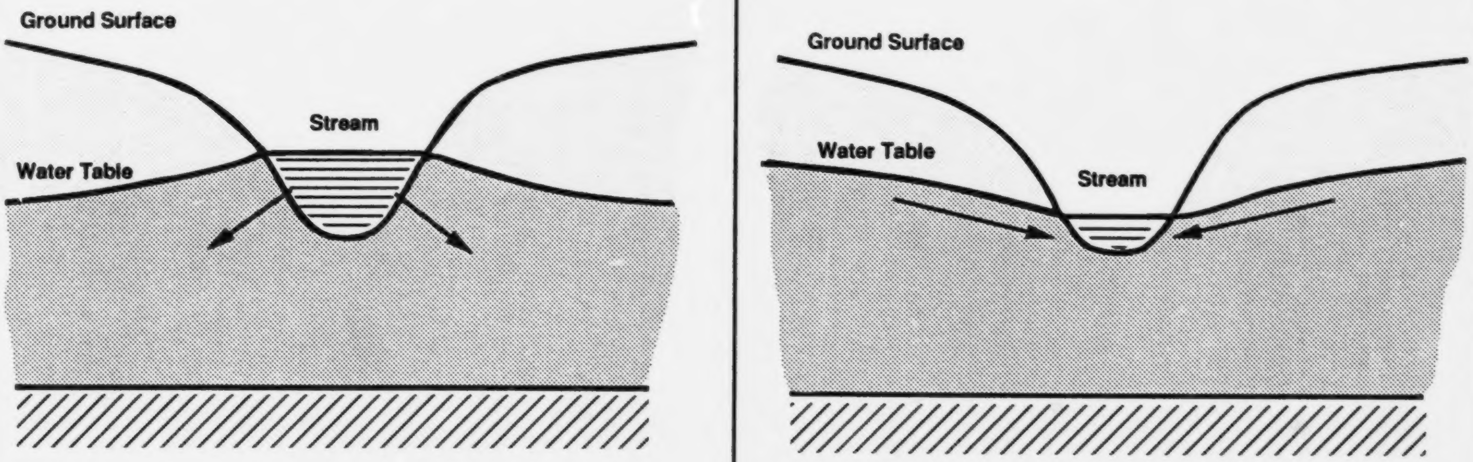
Many factors combine to influence how NAPL and dissolved product move through the subsurface. The following are some of the important factors:

- subsurface stratigraphy, aquifer saturated thickness;
- local topography, location of nearby water bodies;
- location, depth, and pumping rates of nearby wells;
- regional and local groundwater flow direction(s), water table gradients (potentiometric head differences);
- hydraulic conductivity of formation(s); and
- density and viscosity of the bulk product or its constituents.

These data can be used to estimate predict how quickly, and in what directions contaminant plumes will travel. They are also essential in designing an effective remedial system. The importance of these parameters is discussed below.

Groundwater flow direction is important in predicting where a contaminant is likely to migrate and what receptors may potentially be impacted. Horizontal groundwater flow typically follows the contours of the overlying land surface and will tend to be directed from areas of high relief toward streams, lakes and wetlands. Topographic maps can give a very rough approximation of regional flow patterns in an area, where the direction of groundwater flow is considered to be perpendicular to elevation contour lines. However, data from monitoring wells provide a much better estimate of flow direction because groundwater elevations can be measured.

Predicting flow direction would be relatively easy in a homogeneous aquifer with no nearby surface waters or pumping wells that influence the local water table levels. This condition is rare however and most often the site geology will be heterogeneous horizontally and vertically and natural or man-made fluctuations in the water table will occur. Local variability in flow patterns can be caused by seasonal surface water changes, site stratigraphy, and nearby pumping wells. Most surface water bodies interface with groundwater and the flow across the interface can be in either direction. In some cases the flow is always in the same direction (i.e. from the surface water to the groundwater or vice versa). But often, the direction will change seasonally. Figure 10 shows how


Ground Surface
Stream
Water Table
Ground Surface
Water Table
Stream

Surface Water to Groundwater
Flow During Wet Weather Periods

Groundwater to Surface Water
Flow During Dry Weather Periods

Figure 10. Seasonal Variations In Flow Between Groundwater and Surface Water Bodies

seasonal changes in water levels can affect flow patterns. It is important to understand this relationship at a site when assessing the impact of the release.

Site stratigraphy is another important factor in estimating groundwater flow direction. Subsurface formations serve either as confining units or as aquifers. A confining unit or aquitard is characterized by low permeability that does not readily permit water to pass through it despite the fact that it stores large quantities of water (EPA, 1987). A formation serves as an aquifer if its permeability is sufficient to provide a usable quantity of water. Water moves readily through a highly permeable formation such as sands and gravels, which are often productive aquifers. The less permeable silts and clays are common examples of aquitards.

Subsurface formations are typically deposited in horizontal layers and may become folded or faulted or otherwise structurally changed over geologic time. As a result, the thickness and depth below ground surface of formations can vary significantly. However, groundwater movement will generally remain in specific formations (i.e., the more permeable ones). Figure 11 illustrates common geologic conditions.

Subsurface formations can also change character in the horizontal direction. Groundwater follows the path of least resistance and will tend to change direction when the type of formation changes, flowing around a less permeable area and being drawn towards a more permeable one.

Pumping wells change the water table in an aquifer and therefore influence groundwater flow in their vicinity. The greater the pumping rate, the larger the influence the well will have.

Vertical as well as horizontal flow should be considered at a site, including flow between aquifers. The relatively permeable aquitard separating two aquifers can leak, allowing interaquifer groundwater flow. Interaquifer flow can occur from the upper aquifer to the lower, or if the lower confined aquifer has sufficient hydraulic pressure, from lower to upper aquifer. Groundwater, and contaminants, can also migrate between aquifers where wells have been drilled through the aquitard. Figure 12 shows vertical groundwater flow pathways.

The velocity of a contaminant in the saturated zone is a useful parameter to estimate travel times. Dissolved product will generally travel at the same rate as groundwater, although the rate of migration of some dissolved contaminants may be retarded (relative to the average water velocity) due to sorption on soil particles. The extent of sorption will increase with decreasing water solubility of the contaminant, and with increasing organic carbon content and/or surface area of the soil. Floating NAPL will generally flow at a rate different than the underlying aquifer. The difference in velocity between water and petroleum products is due to viscosity and density differences.

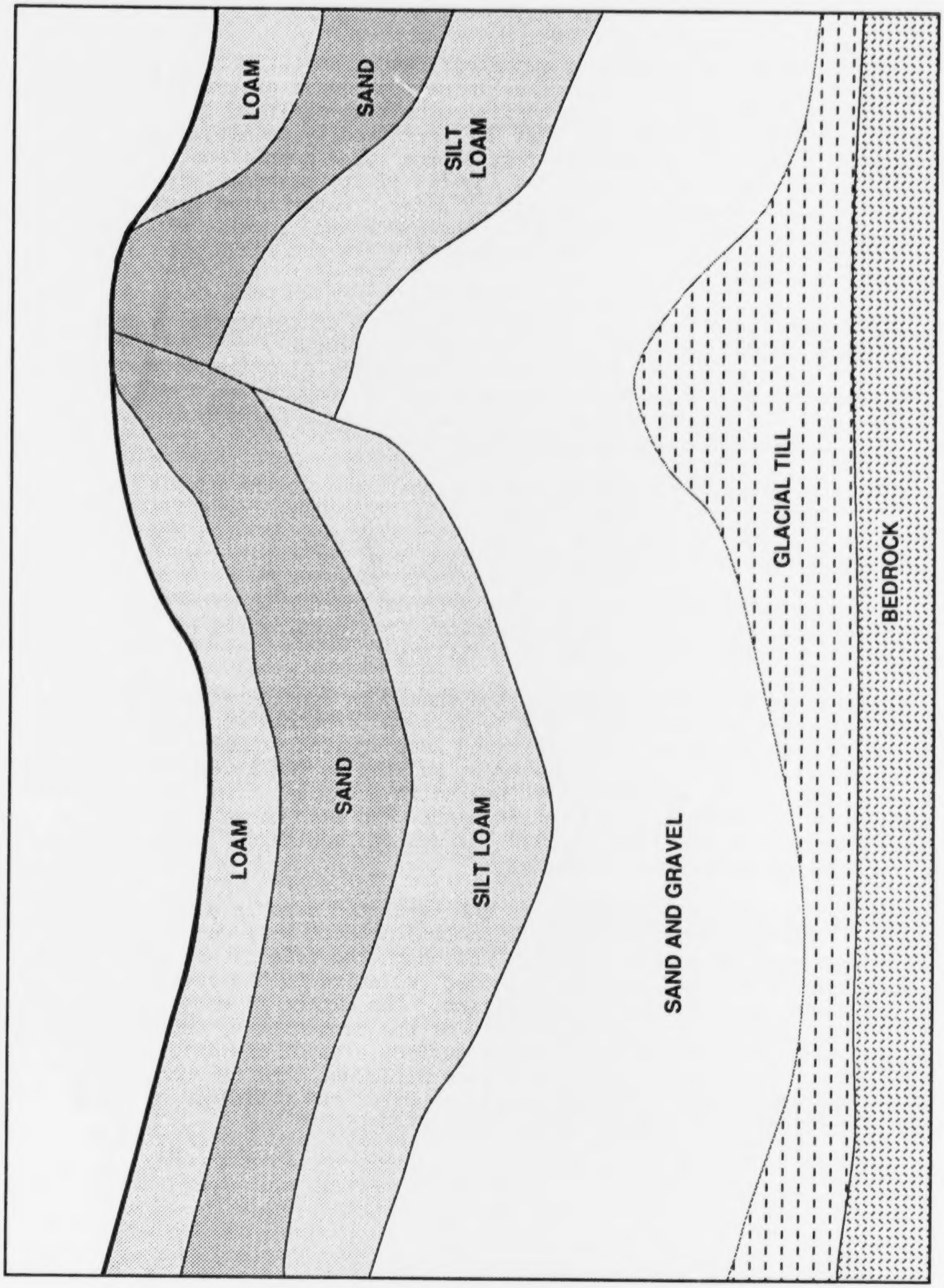

LOAM
SAND
SILT LOAM
LOAM
SAND
SILT LOAM
SAND AND GRAVEL
GLACIAL TILL
BEDROCK

Figure 11. Variability of Subsurface Stratigraphy

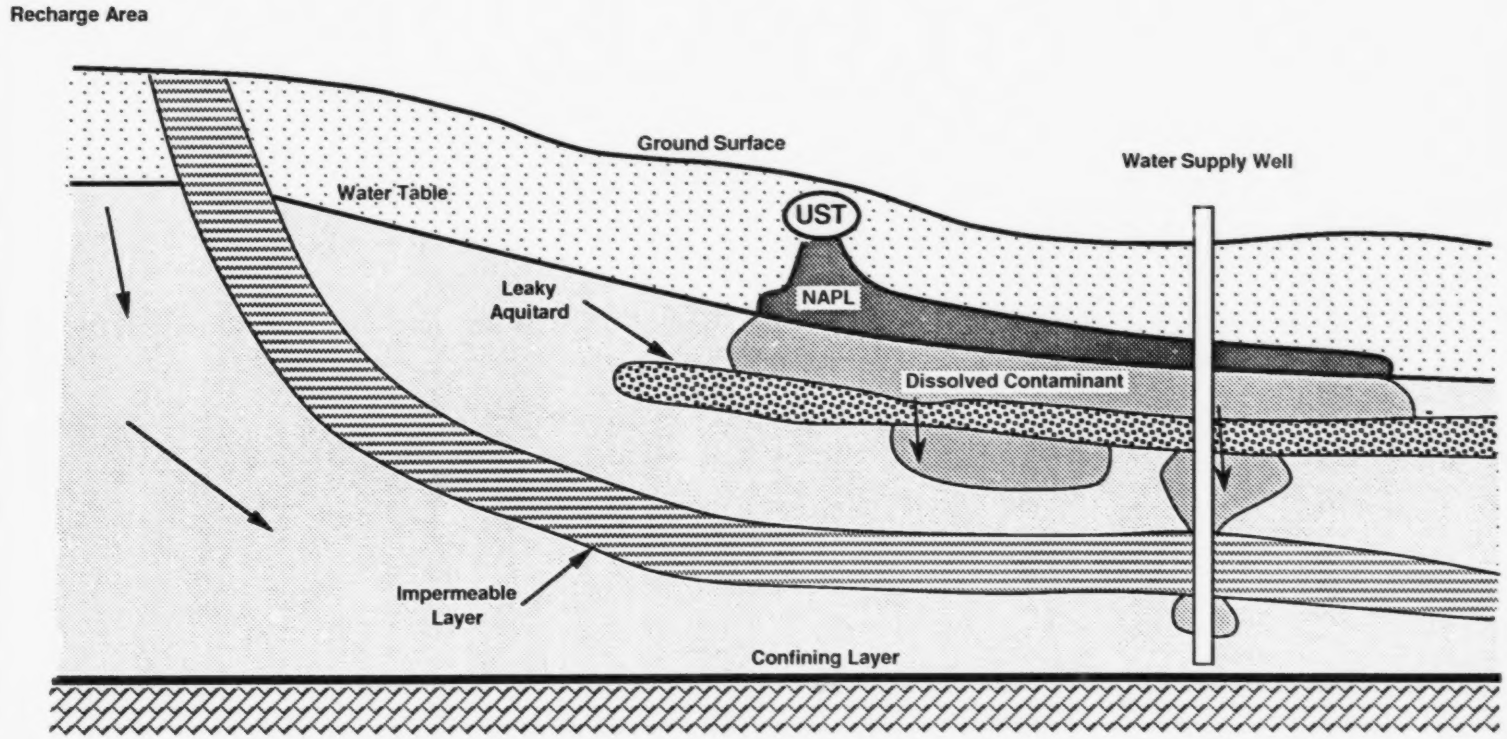

Recharge Area
Ground Surface
Water Supply Well
Water Table
UST
NAPL
Leaky
Aquitard
Dissolved Contaminant
Impermeable
Layer
Confining Layer

Figure 12. Interaquifer Contaminant Transport

The velocity of a fluid through a porous medium such as soil can be represented by the equation:

$$v = ki/n \qquad (5)$$

where: v = velocity of groundwater (cm/sec);
k = fluid conductivity (cm/sec);
n = effective porosity of the formation (dimensionless); and
i = gradient of the water table or floating NAPL (cm/cm).

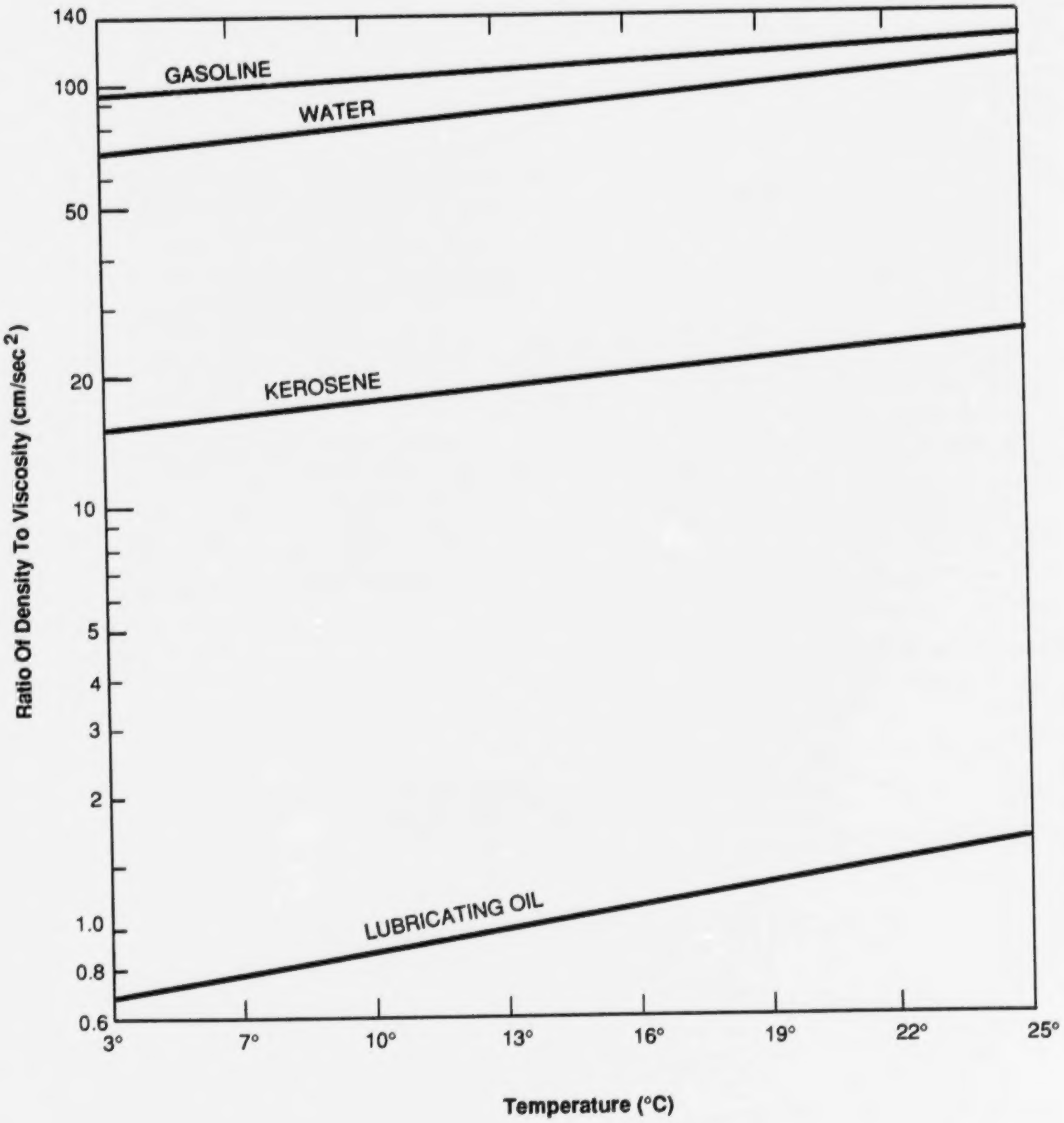
Porosity is the ratio between the total volume of air space and the total soil volume, however not all of the air volume in a soil is available for transport of fluid. Materials such as clay can have a high porosity but a fairly low effective porosity because many of the pore spaces are not interconnected. The effective porosity of the formation should be used in velocity calculations to reflect this. The hydraulic gradient is the slope of the water table, where the slope is defined as the change in water level per unit distance in the direction of flow. For estimating the velocity of floating NAPL, using the hydraulic gradient is not likely to introduce significant errors.

The conductivity of a fluid is a measure of the ease with which it will flow through a porous medium and varies for different fluids (e.g. water flows through a given soil more easily than a viscous oil). The conductivity of a fluid is directly proportional to its density and inversely proportional to its viscosity. Conductivity is also affected by temperature, because viscosity decreases as temperature increases. Figure 13 compares the density to viscosity ratios for several petroleum products and water as they vary with temperature. As the density to viscosity ratio increases, fluid mobility increases. Note that the mobility of gasoline in the subsurface is similar to water but lubricating oil is relatively immobile.

Figure 14 shows an example of how the travel time of groundwater can be estimated. When estimating velocity or travel time for dissolved contaminant, the hydraulic conductivity (i.e., water conductivity) is appropriate to use in Equation (5). But if the velocity of floating NAPL is needed, conductivity of the particular contaminant should be used. This is an important point to consider when developing an understanding of the potential impacts of a release. For example, if a relatively immobile product such as No. 2 fuel oil is released, the resulting dissolved contaminants in the groundwater will move at roughly the same velocity as the groundwater. However, the bulk fuel oil on the water table will move much more slowly than the groundwater. If the release were gasoline, dissolved contamination and the bulk liquid would both move at about the same velocity, and the bulk liquid may travel somewhat more quickly. The immediate goals of remediation in these two scenarios may be quite different. As shown in Figure 3, when goals are different, the type of remedial response will likely be different as well.

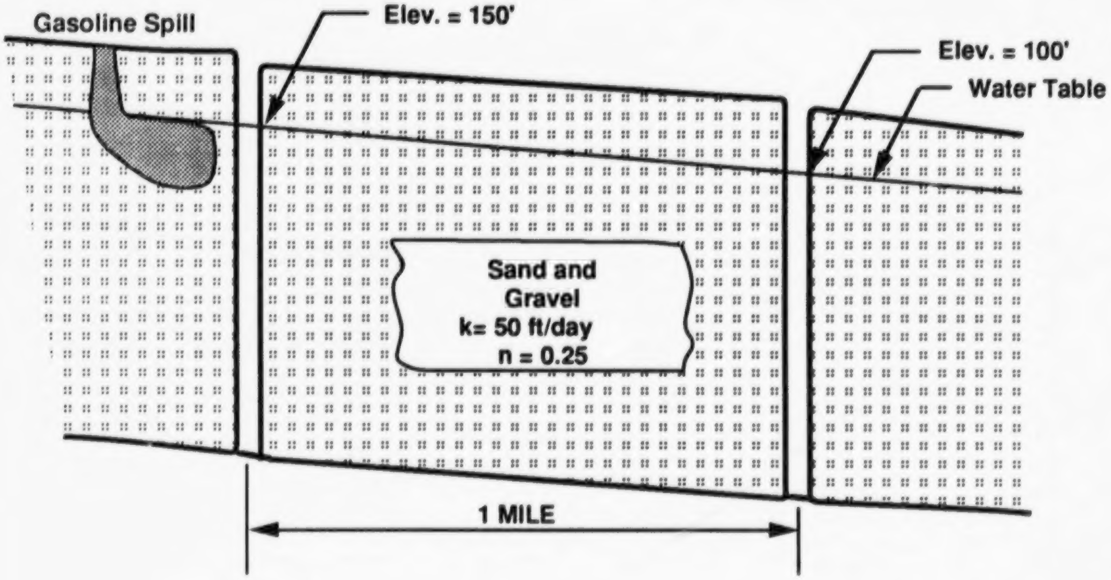
SETTING REMEDIATION GOALS

An effective remediation plan must adequately address all phases of a clean-up. Complete restoration at a release site is desirable, but not all



Source: Adapted from CH2MHill, 1989

Figure 13. Density-to-Viscosity Ratios for Water and Hydrocarbon Products as a Function of Temperature


Gasoline Spill
Elev. = 150'
Elev. = 100'
Water Table
Sand and Gravel
k= 50 ft/day
n = 0.25
1 MILE

Gradient = i = (150 - 100) / 5,280 = 0.009 ft/ft
Velocity = K i / n = 50 (0.009) / 0.25 = 1.8 ft/day
Travel time = 5,280 / 1.8 = 2933.3 days = 8.0 years

Figure 14. Estimating Groundwater Travel Time

sites require a remediation program designed to restore the site to a pristine condition. The unique conditions at each release site must be considered to set realistic remediation goals. This subsection discusses various remediation goals and some of the types of the site conditions that may influence goal selection.

If the goal of remediation is to return the site to pre-release conditions, there are several typical clean-up phases that are likely to be implemented. Emergency responses are a first priority to ensure that no immediate health or safety threat exists. Containment of the dissolved and NAPL contaminants limits the extent of contamination and facilitates restoration efforts. Removal and/or treatment of subsurface contamination must be accomplished and finally, a site monitoring program should be set up to detect any changes that would suggest restoration was incomplete.

The time-frame over which the components of remediation are implemented will vary from site to site. Short- and long-term objectives should be outlined that define what order the various stages should be implemented. Emergency measures should always be addressed quickly, but implementation of other aspects of remediation may not be as urgent if contaminant mobility is limited or the impact to receptors is determined to be minimal. A prioritization scheme should also be evaluated so that the most urgent or important tasks are accomplished first. For example, containment of the dissolved plume may take precedence over containment of NAPL because it may represent a more immediate threat to a drinking water supply. Initial design of a containment system would focus on preventing dissolved contaminant migration.

Because various site activities will be implemented at different times, it is important to consider how initial activities may affect future ones. For instance, saturated zone clean up may be implemented before unsaturated zone clean up and the technology used to treat the saturated zone may influence what technologies will be successful in the unsaturated zone. Also, contamination from the unsaturated zone can migrate to the saturated zone increasing the total length and cost of treatment. Such problems can be avoided with effective planning.

The objective or approach to a remediation plan can be put into three broad categories: 1) no active remediation; 2) containment of subsurface contaminants; and 3) treatment and/or removal of contaminants at the site. The approach taken at a particular site will depend on many different factors, including the pre-existing groundwater quality, the potential impact to vulnerable receptors, the feasibility of removing contaminants, and regulatory requirements. An approach other than complete restoration of the site should be preceded by a careful evaluation of site conditions and be made in conjunction with regulatory officials. Each of the three categories is described below and some of the site conditions which might lead to their selection is discussed.

No-Action Alternative - Site conditions may lead to the decision to take no immediate action at a site. The no-action alternative may be a short term condition, in effect only until remediation efforts are fully evaluated. This might apply if local drinking water supplies or other vulnerable receptors were far enough removed from the site to warrant no immediate action. And in some cases, well-head treatment of contaminated drinking supplies has been found to be a more cost-effective alternative to containment and/or treatment of the release. On the other hand, it may be decided that no action is required at the site for the foreseeable future. If the site is in an industrial area where groundwater quality was poor before the release occurred, an extensive remediation effort may not be warranted.

Containment - Containment involves preventing further migration of subsurface contaminants so that additional areas are not impacted by the release. Containment may be the primary objective of remediation if treatment or removal of the contaminants is not considered feasible or there is difficulty in selecting or designing an effective treatment method. Containment may also be a short term objective if permitting problems delay implementing an above-ground treatment scheme. The long term objective in this case would be contaminant removal once the proper permitting was obtained.

Treatment and/or Removal of Contaminants - Implementation of a remedial plan that will return the environment to pristine conditions (or at least to pre-release conditions) is a lofty goal. This level of clean up is very difficult to achieve, especially for sites with large releases and complex stratigraphy. Regulatory officials may require that some percentage (e.g. 99%) of all contaminants must be removed or state legislation may mandate minimum groundwater quality levels. Such requirements will dictate complete restoration as a goal at the site, typically at tremendous cost.

A study of Superfund sites (CH2M Hill, 1989) where groundwater extraction techniques were used found that contaminant removal to health-based standards is possible under favorable site conditions, but the time-frame for completion is often underestimated. The total clean up time for sites where large releases have occurred is likely to be measured in decades. Favorable site conditions are not common, and contaminant removal to health-based standards may be difficult at many sites. The difficulty in meeting the stringent clean-up requirements results in remediation continuing long after targeted clean-up finish dates have passed. The main causes for delays in completing remediation are poor delineation of the contaminant plumes and the presence of residual liquid contaminants in the groundwater which are not readily removed from the subsurface.

Summary

The site assessment outlined in this section should enable the user to develop a conceptual understanding of the site and to reasonably predict how a given contaminant is likely to behave in the subsurface. In addition, the user should be familiar with some of the important issues in deciding what level of clean up is required and the time frame over which remediation efforts should take place. The next section presents several technologies that can be used to accomplish remediation goals and helps in evaluating which are likely to be most effective at a given site.

SECTION 3

TECHNOLOGY SELECTION

INTRODUCTION

There are a variety of ways to address a release of petroleum product into the environment. These range from no immediate action to a full scale remediation effort designed to restore the environment to pre-release conditions. With the exception of the "no-action" alternative, each approach will involve using one or more of the available clean-up technologies. The approach best suited to a particular site will depend on the goals of remediation and unique site conditions.

A typical remediation plan that has restoration to pre-release conditions as the goal would likely have three main components: 1) containment of NAPL and/or dissolved product; 2) NAPL removal; and 3) dissolved product removal. If the goal of remediation is only to prevent the contaminants from moving away from the site, then the last two components would be unnecessary. As shown in Figure 3, this section identifies and describes technologies that are effective in addressing the various goals of remediation. Presented at the end of the section is a discussion of how the various technologies can be used in combination to enhance the overall remediation effort.

This manual focuses on technologies that are commonly used and/or well understood. Promising new technologies are discussed briefly at the end of this section. Outlined below are the technologies covered herein.

- Containment Methods - Preventing migration of contaminants can involve NAPL and/or dissolved product. Trench excavation is effective only for containment of NAPL. Pumping wells can be installed to contain both NAPL and dissolved product.

- Recovery of NAPL - NAPL recovery is often accomplished in conjunction with either trench excavation or pumping well installation. Various types of removal equipment can be used once the NAPL has been controlled. NAPL recovery can also be accomplished with or without implementing a containment system by using vacuum extraction.

- Dissolved Product Removal - Groundwater treatment methods can be either above-ground or in situ. The above-ground methods covered in the manual are air stripping and carbon adsorption. In-situ treatment is where contaminants are treated or removed without disturbing the subsurface or bringing groundwater above ground. The only in-situ groundwater treatment method covered in detail in this manual is biorestoration. Air sparging, another in-situ groundwater technology, is only briefly discussed.

For each technology described herein, factors are presented that should be considered when evaluating the technology at a given site. These critical success factors (CSFs) are parameters that influence the likelihood of success of a particular method. For example, high contaminant volatility is a CSF for air stripping. These CSFs can be used to assess the likely effectiveness of each technology at a particular site. Finally, other advantages and disadvantages that can influence technology selection are discussed.

A worksheet has been provided for each technology to help the user evaluate the likely success of the technology at a particular site. The CSFs important for that technology are listed. Completed worksheets provide insight as to which technologies are likely to be effective, and more importantly, which are not. The three right hand columns of each worksheet provide ranges of values for the CSFs that suggest whether a technology is "less likely," "somewhat likely," or "more likely" to be effective. A column is provided for the user to write down the values for the CSFs at the site of interest. For each CSF, the user determines which of the three "likelihood" ranges the site falls. If most of the CSFs fall into the "less likely" column, another technology may be better suited to cleaning up the site. If the CSFs are fairly evenly distributed among the three columns, other factors can be considered that can help in the assessment (i.e. can a parameter be enhanced to increase the likelihood of success?).

The importance of each CSF in evaluating the effectiveness of a given technology is not the same. Some CSFs will play a greater role than others and in some cases, a single CSF may outweigh all others in importance at a given site. For example, if the depth to the water table is very large, trench excavation will not be feasible even if all other CSFs are favorable. However, it is impossible to attach a quantitative weighting system to the CSFs because the relative importance of the CSFs varies from site to site (i.e., what is relatively important at one site might be less so at another). To address this issue, a discussion of the CSFs accompanies each worksheet followed by a brief discussion of the relative importance of the CSFs.

Both cost-effectiveness and technical feasibility are considered in the worksheets. For example, the "depth to groundwater" CSF for trench excavation (See Table 12) shows that if the water table is greater than 5 meters below ground surface, success is less likely. This is based on the fact that the cost of trench excavation increases significantly at depths greater than 5 meters. Trench excavation is technically feasible under deep groundwater conditions, but the high costs make other methods comparatively more attractive. The CSFs in the worksheets may target either the technical feasibility or the cost-effectiveness of the given technology, and in some cases, both.

The Appendix of this manual provides examples of how to use the worksheets. Values for all applicable CSFs are assumed for a hypothetical release situation, and four different worksheets are completed using the CSF data. Along with each completed worksheet is a brief interpretation of the results. Included at the back of this manual are copies of each worksheet in the manual. These can be detached and copied, with the copies being used for any number of release sites.

CONTAINING NAPL AND/OR DISSOLVED CONTAMINANT

Preventing further migration of subsurface contaminants is often a major part of a remediation effort and may be the primary goal of the project. Containment lessens the potential threat to nearby surface water and groundwater supplies. It can also serve to consolidate widely spread contaminants into a smaller area, facilitating their removal. The two containment methods presented in this manual, trench excavation and pumping well installation, are described below.

Trench Excavation

A very simple way to prevent migration of floating NAPL is to dig a trench downgradient of the plume. As the NAPL reaches the trench, it can be intercepted, removed, and disposed of, thereby preventing migration beyond the trench. Besides its simplicity, trench excavation is a useful containment method because it can be implemented quickly. However, it is not feasible in regions such as the Southwest where depth to the water table is often great. It is also not as effective in containing dissolved contaminants or denser than water NAPL, which may pass below the trench.

At a minimum, implementing a trench excavation containment system requires the following information:

- direction of plume flow;
- depth to water table;
- down-gradient and lateral extent of the NAPL plume; and
- location of underground utilities that may interfere with the excavation.

Figure 15 shows schematic plan and section views of a typical trench excavation operation. The trench is dug to a depth several feet below the water table and should be long enough to intercept the full lateral extent of the plume. The trench must also be perpendicular to local groundwater flow direction. As the plume moves toward the trench, free product accumulates in the trench and can be recovered manually or with pumps. To prevent the free product from moving past the trench, an impermeable liner can be placed on the downstream side of the trench. To increase the rate of recovery of free product, pumps may be used to lower the water table. As the water table is lowered, the hydraulic gradient toward the trench is increased and free product is drawn more quickly to the trench. However, care must be taken to ensure that the water table is not lowered below the bottom of the trench, allowing NAPL to pass by.

When trenches are used to contain and remove free product, removal efforts must be continuous. Otherwise the product will migrate to the ends of the trench and possibly pass the impermeable baffle.

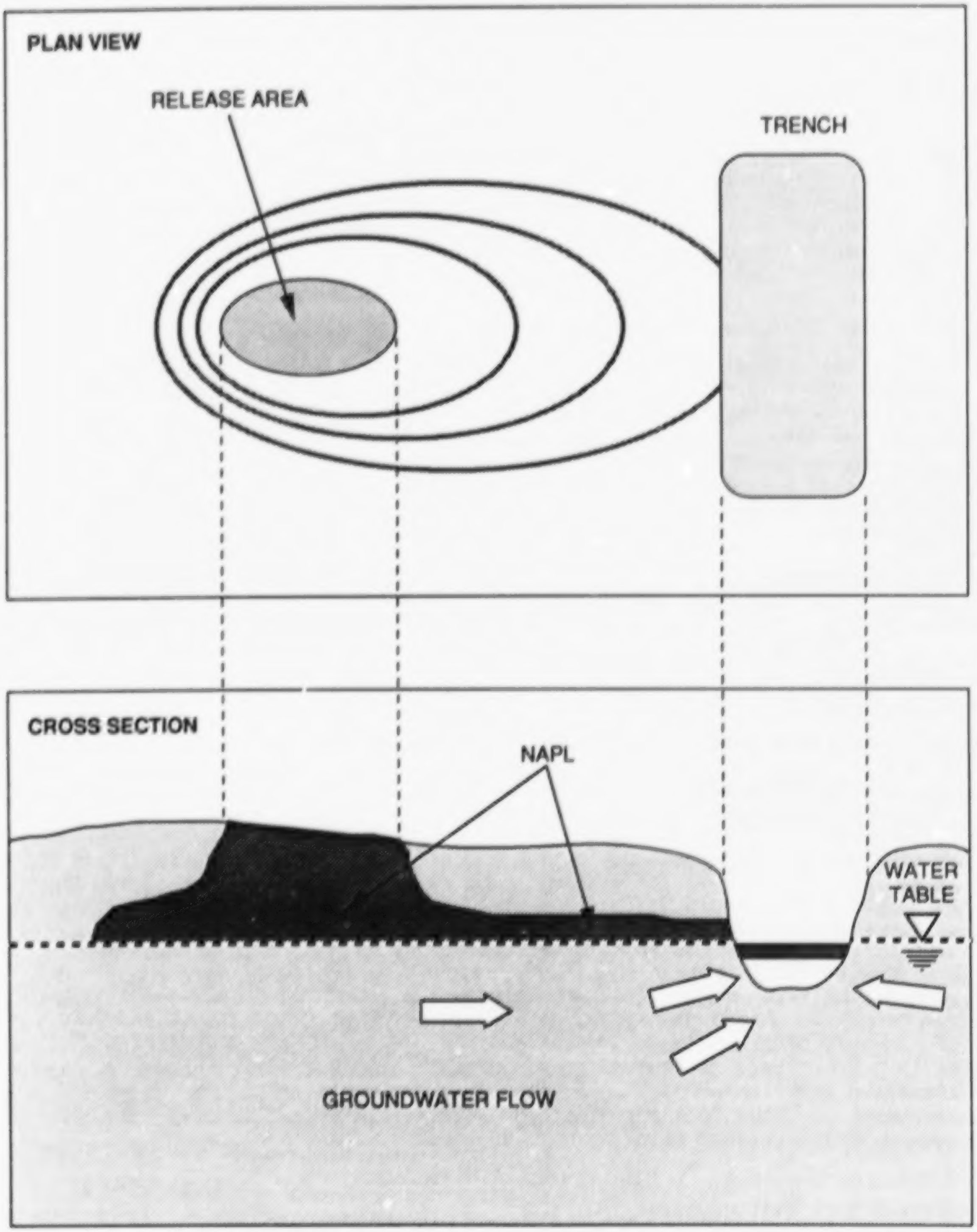

PLAN VIEW
RELEASE AREA
TRENCH
CROSS SECTION
NAPL
WATER
TABLE
GROUNDWATER FLOW

Figure 15. Schematic Diagram of Trench Excavation

Evaluating Trench Excavation as a Containment System

Table 12 lists factors to consider in evaluating the likely effectiveness of trench excavation as a containment system at a particular site. Each of the factors in Table 12 are discussed below.

Knowing the time since release and the size of the release can give an idea of how far the contaminant has traveled in the subsurface. A widely dispersed plume will require a longer trench, increasing the cost of the system. The greater the size of the release and the more time that has elapsed since the release, the greater the areal extent of the plume will be. Also, the longer ago the release occurred, the more likely significant amounts of contaminant have dissolved into the groundwater. Dissolved contaminants generally are not contained using this method.

The depth to groundwater should be known prior to selection. Trench excavation more than 5 meters below the ground surface becomes increasingly expensive because special equipment must be used. This equipment is not always readily available and may limit the usual quick response time of excavation. In addition, deeper trenches are less stable and usually must be supported. Trenches that must be maintained for long time periods may require protection such as rip rap or wood sheeting along the slopes to prevent erosion.

The soil formation at the site should be relatively cohesive and self-supporting. Otherwise the trench walls may be difficult to maintain. In densely populated or commercially developed areas, above- and below-ground structures may interfere with excavation or placement of the trench.

Trench excavation is only effective at containing NAPL floating on the water table. Therefore, the type of contaminant released must be known. If denser than water, the contaminant will sink to the bottom of the aquifer where it cannot be recovered using this method.

Relative Importance of CSFs

From a cost perspective, depth to groundwater and the presence of interfering structures are the CSFs most likely to prevent or prohibit use of this method. From an engineering perspective, the liquid density of the contaminant is very important, since a "denser than water" compound is not likely to be contained effectively with a trench.

Pumping Well Installation

Pumping wells are an effective and commonly used method for containing a contaminant in the saturated zone. Unlike trenches, pumping wells are effective in containing dissolved contaminants and denser than water NAPL as well as floating NAPL. The basic concept behind this method is to artificially lower the water table at the site, drawing local groundwater and contaminants to the well. This not only prevents the contaminant plume from migrating but also can concentrate the floating NAPL, if present, in a single area, facilitating recovery.

Table 12. Worksheet for Evaluating the Feasibility of Using Trench Excavation to Contain Floating NAPL

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
• **Amount Released**	gallons		Large (>500,000) ○	Medium (50,000-500,000) ○	Small (<50,000) ○
• **Time Since Release**	months		Long (>12) ○	Medium (1-12) ○	Short (<1) ○
SITE - RELATED					
* • **Depth to Groundwater**	meters		Deep (>5) ○	Medium (1-5) ○	Shallow (<1) ○
• **Stability of Soil Formation**	-		Unstable ○	-	Stable ○
* • **Presence of Interfering Structures**	-		Present ○	-	Not Present ○
CONTAMINANT- RELATED					
• **Liquid Viscosity**	cP		High (>2) ○	Medium (1-2) ○	Low (<1) ○
* • **Liquid Density**	g/cm^3		High (>1) ○	-	Low (<1) ○

OTHER CONSIDERATIONS

- Trench excavation can generally be implemented quickly.
- Costs for this method are typically lower than for other methods
- Denser than water contaminants cannot typically be contained with trench excavation

* CSFs denoted with an asterisk are typically more important than other CSFs

The two most important considerations in this method are well location and pumping rate. To determine location and pumping rate, site hydrogeology and the vertical and areal extent of contamination must be known. Each pumping well has an zone of contribution (ZOC), within which local groundwater will flow towards the well. For a given soil formation, the size of the ZOC increases as the pumping rate increases. To prevent contaminant migration, the well configuration and pumping rate must be such that the contaminant plume is completely contained within the well's ZOC. If the contaminant plume is very large or soil conditions prevent adequate pumping rates, several wells may be required to fully contain the plume. Figure 16 shows a typical pumping well used to prevent contaminant migration.

Difficulties with this method arise at sites with complex stratigraphy because hydraulic conductivity varies for different types of formations. Estimating the average hydraulic conductivity of such a site is difficult, and the extent of the ZOC will not be equal in all directions. This could result in poor location of wells. Figure 17 shows how stratigraphy can influence pumping well containment.

Local variations in the groundwater table also make it difficult to accurately delineate the ZOC of the containment wells. As described in Section 2, flow direction between surface water bodies and the adjacent groundwater can change seasonally. This would cause the ZOC of a pumping well to change also. Nearby drinking water wells also influence the natural water table gradient and must be taken into account to accurately delineate the pumping well ZOC.

The time-frame for implementing a pumping well system should be considered. Often a pump test, lasting days to weeks, must be conducted in order to accurately determine hydraulic conductivity. Difficulties may arise in accurately delineating the ZOC causing additional delays in implementing the system. At some sites, it may be crucial that a containment system be deployed quickly before the contaminant plume can reach a vulnerable receptor.

It is desirable to maintain a constant pumping rate for this method. If the pumping rate is not kept constant, fluctuations in the water table can cause NAPL to be trapped below the water table which can present recovery problems. Also, if the pumping rate is decreased, the water table may rise sufficiently to allow the outer edge of the plume to resume migration from the site.

Determining the ZOC of a Well

To determine whether a well is properly located and an adequate pumping rate has been applied, the ZOC of the well must be estimated. At some sites, this can prove to be very difficult and the accuracy of the estimate will depend on the accuracy of the site assessment. Javandel and Tsang (1986) present a method for determining the ZOC of single wells or groups of wells based on the following parameters:

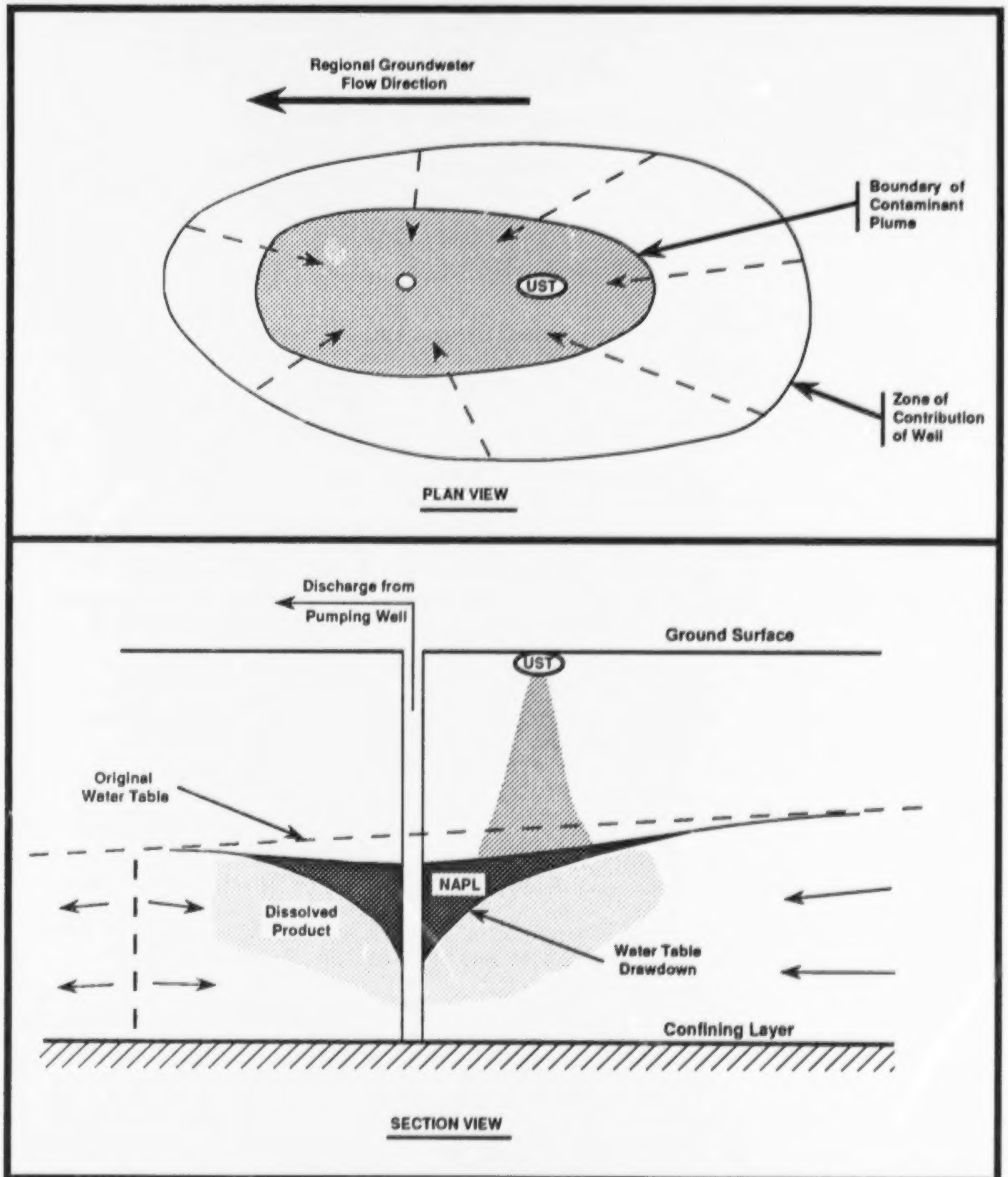

Regional Groundwater Flow Direction
Boundary of Contaminant Plume
UST
Zone of Contribution of Well
PLAN VIEW
Discharge from Pumping Well
Ground Surface
UST
Original Water Table
NAPL
Dissolved Product
Water Table Drawdown
Confining Layer
SECTION VIEW

Figure 16. Schematic Diagram of a Pumping Well Used to Contain Petroleum Products in the Saturated Zone

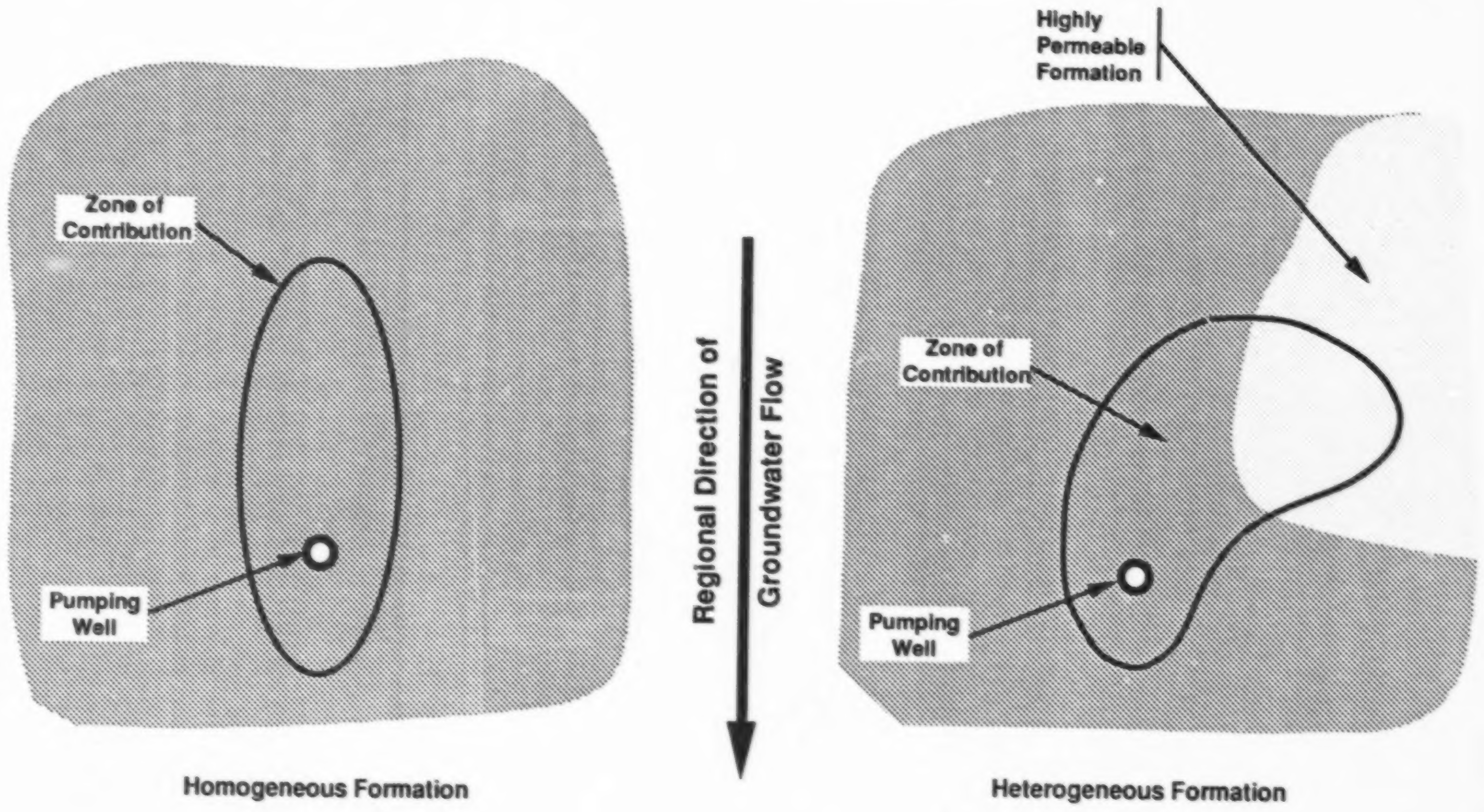

Zone of Contribution
Pumping Well
Homogeneous Formation
Regional Direction of Groundwater Flow
Highly Permeable Formation
Zone of Contribution
Pumping Well
Heterogeneous Formation

Figure 17. Distortion of the Zone of Contribution of a Pumping Well Due to a Heterogeneous Formation

- pumping rate;
- hydraulic conductivity;
- aquifer thickness; and
- hydraulic gradient.

The hydraulic conductivity, aquifer thickness, and hydraulic gradient are identified during the site assessment. An appropriate pumping rate can then be determined that will induce a ZOC containing the entire contaminant plume. The equations used in this method are fairly complex and will usually require the use of a computer. For a more detailed coverage of this method, the reader can consult Todd (1980) or Freeze and Cherry (1979) as well as the previously mentioned source.

Alternatively, a simplification of the above method approximates the elliptical shape of the actual ZOC with a rectangular shape. The up-gradient, down-gradient, and lateral extent of the ZOC is estimated based partially on the boundary conditions of the equations used in the preceding method and partially on steady state theory. Under steady state theory, the area of a ZOC of a well with a constant pumping rate is proportional to the rate of recharge available through infiltrating rainfall. Recharge rates can be estimated fairly easily. Once the total area of the ZOC is known, the approximate shape of the ZOC can be delineated. This method can prove useful for a preliminary assessment, but caution should be exercised and a factor of safety applied to the calculations commensurate with the confidence the user has in the accuracy of the site assessment. EPA (1987c) discusses this method in greater detail.

Evaluating Pumping Wells as a Containment System

Table 13 lists factors to consider in evaluating the likelihood of using pumping wells as a containment method. The importance of each of the factors is discussed below.

The amount of petroleum product released and the time since release may play roles in choosing a containment system. For larger and/or older releases, the areal extent of the resulting NAPL plume will be greater, and a larger trench will be required to effectively contain the plume. Pumping wells may be more cost-effective than trenches, if very long trenches are required.

An important consideration in designing an effective containment system using pumping wells is site stratigraphy. For aquifers in homogeneous formations and with flat, non-fluctuating water tables, it is fairly easy to estimate the ZOC of a well. However, it is difficult to accurately estimate the effect of a pumping well on the surrounding groundwater at sites with complex stratigraphy. Under such conditions, it is necessary to conduct extensive field studies to better understand the site. These field studies take time, and implementation of the containment system will be delayed allowing the plume to continue to migrate.

TABLE 13. Worksheet for Evaluating the Feasibility of Using Pumping Wells to Contain NAPL and/or Dissolved Contaminant in the Saturated Zone

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
• **Amount Released**	gallons		Small (<50,000) ○	Medium (50,000-500,000) ○	Large (>500,000) ○
• **Time Since Release**	months		Short (< 1) ○	Medium (1 - 12) ○	Long (>12) ○
SITE - RELATED					
* • **Site Stratigraphy**	-		Complex ○	- ○	Simple ○
• **Depth to Groundwater**	meters		Shallow (<5) ○	-	Deep (>5) ○
CONTAMINANT- RELATED					
• **Liquid Density**	g/cm^3		Low (<1) ○	-	High (>1) ○
• **Liquid Viscosity**	cP		High (>2) ○	Medium (1 - 2) ○	Low (<1) ○

OTHER CONSIDERATIONS

- Installation of pumping wells can be delayed due to difficulties in delineating well ZOCs.
- Extracted groundwater must often be disposed of or treated.
- This may be the only effective containment method at sites where depth to water table is great.

* CSFs denoted with an asterisk are typically more important than other CSFs

The depth to groundwater at a site is important from a cost viewpoint. Pumping wells can be used at most sites regardless of depth to groundwater, but they generally become much more cost-effective than trenches if the depth to groundwater is greater than 5 meters.

Petroleum products that are heavier than water will sink below the water table and migrate towards the bottom of the aquifer. Those products can be contained with pumping wells, but generally not with trenches. Therefore, the liquid density of the petroleum products should be considered when evaluating containment systems. The liquid viscosity of the bulk liquid is somewhat less important. High viscosity products flow less easily than lower viscosity products, and it is generally more difficult to control the movement of products with higher viscosity. However, a highly viscous product will typically be less mobile in the subsurface, and containment may not be as urgent.

Relative Importance of CSFs

The ultimate success of this method depends on how accurately groundwater flow patterns can be identified and controlled. This requires a good understanding of site stratigraphy, which is the most important CSF in Table 13 in terms of technical performance. Although not listed as a CSF, another important consideration is the degree of immediacy associated with implementing a containment system. Because pumping wells often take longer to install, trenches may be preferable when containment is more urgent.

Choosing a Containment System

Tables 12 and 13 can be used to compare trench excavation versus pumping wells at a given site. Some of the major advantages and disadvantages of the two methods are discussed below.

- Time-Frame - Trenches can generally be excavated quickly. A pumping well can sometimes be installed quickly as well, but certain site conditions can delay implementation. If the site stratigraphy is complex, the proper placement of the well and the optimal pumping rate may require additional time to determine.

- Depth to Water Table - Trench excavation is typically not effective at sites where the depth to water table is greater than 5 meters (15 feet). Pumping wells can be effective at at a wide variety of depths.

- Size of Contaminant Plume - Very large releases and widely spread plumes are often better contained with pumping wells than trenches. However, if the soil formations have a low permeability (e.g., clays), the ZOCs for recovery wells may be very small. Under such conditions, the number of wells required to contain the release could improve the attractiveness of trenches.

- Location of Contaminants in the Saturated Zone - Trenches are used primarily for floating NAPL plumes. Dissolved contaminants or denser than water contaminants will generally pass underneath the trench. Pumping wells are more flexible in that they can be used to contain "denser than water" contaminants as well as "floaters."

- Proximity of Above- or Below-Ground Structures - It may be difficult to dig a trench in a highly developed area, where there are many homes or buildings. Pumping wells require much less space and are often better suited to these areas. The presence of underground utilities is also more likely to present a problem for trenches than for pumping wells.

- Increased Soil Contamination - One drawback to pumping wells is that as the water table is depressed, more contaminants become sorbed to soil particles as the floating NAPL moves downward with the water table. Trenches avoid this problem.

RECOVERY OF FLOATING NAPL

Recovery of NAPL floating on the water table is a common part of site remediation when a release of petroleum products reaches the saturated zone. This is particularly true of large releases. The timely removal of floating NAPL limits the movement of contaminants to the dissolved and sorbed phases, which may be more costly to remove than floating NAPL. In addition, recovered NAPL may be of commercial value and proceeds from the recovered product can help defray clean-up costs.

There are several methods used to recover floating NAPL. The most common of these use a pumping or oil/water separation scheme, depending on the containment method implemented at the site. Some type of containment system is usually needed to aid in these types of NAPL recovery to maintain an adequate supply of recoverable product. Where the floating NAPL layer is very thick (there have been documented cases of NAPL over 15 feet thick) recovery can continue for extended periods without a containment system being installed. Another recovery method that is not as common but has been used effectively is vacuum extraction. Each of these methods is discussed below. Discussion of NAPL recovery associated with the two containment systems of the previous subsection is limited to the types of recovery equipment commonly used with each. A more detailed discussion of vacuum extraction is presented.

Hazards Associated with NAPL Recovery

The release of petroleum products, which are often highly volatile, creates the potential for fire and explosion hazards. At a minimum, the following steps should be taken to reduce the potential for fire or explosion at a site:

- assess the potential hazards;

- isolate the danger areas;

- eliminate sources of ignition, particularly where pumps or other recovery equipment is concerned; and

- ventilate confined areas.

A remediation program should always be preceded by a health and safety plan that considers in detail fire and explosion hazards that might be encountered.

NAPL Recovery with Trench Excavation

The two most common types of equipment used to recover NAPL from trenches are skimmers and filter separators. Skimmers are designed to float and automatically pump NAPL off the water surface. Some are equipped with sensors that can detect petroleum products and only operate when a sufficient thickness of NAPL is present. Filter separators work much like skimmers except that the filter, which allows only petroleum product to pass through it. This device floats in the trench while the pump is maintained above-ground. For either type of equipment, the recovered NAPL must be stored in recovery drums for treatment or disposal.

NAPL Recovery with Pumping Well Installation

The two main types of recovery systems involving pumping wells are single pump and dual pump systems. In single pump systems, one pump is used to both contain the plume and recover NAPL. For dual systems, one pump is used to create a depression in the water table and another to remove NAPL floating on water table. Figure 18 shows typical single pump and dual pump recovery systems.

Single Pump Method

In this method, both the floating NAPL and groundwater are recovered through a single pipeline and stored or treated at the surface. NAPL can be removed from the groundwater/NAPL mixture by way of oil/water separation equipment.

Single pump systems are best suited for small volume spills and sites with shallow groundwater tables. A major drawback to this method is that groundwater and NAPL are mixed together during the recovery process, resulting in two obstacles to treatment. First, the groundwater/NAPL mixing that occurs during recovery makes it more difficult to separate the two above ground. Second, because the groundwater and NAPL are not kept separate during recovery, large volumes of groundwater must be treated that may have previously been unpolluted.

Dual Pump Method

In this method, two pumps are installed in a recovery well. The lower pump is used to depress the local groundwater table, and serves to both prevent further migration of NAPL and concentrate the NAPL in a smaller area. The upper pump is positioned so that floating NAPL is recovered while the pump is operating. Each of the pumps is typically equipped with sensors to ensure that each of the pumps operates as desired.

The dual system is more commonly used than the single pump method, primarily because mixing of groundwater and NAPL is avoided. Also, the NAPL recovery pump need only be operating when a significant thickness of

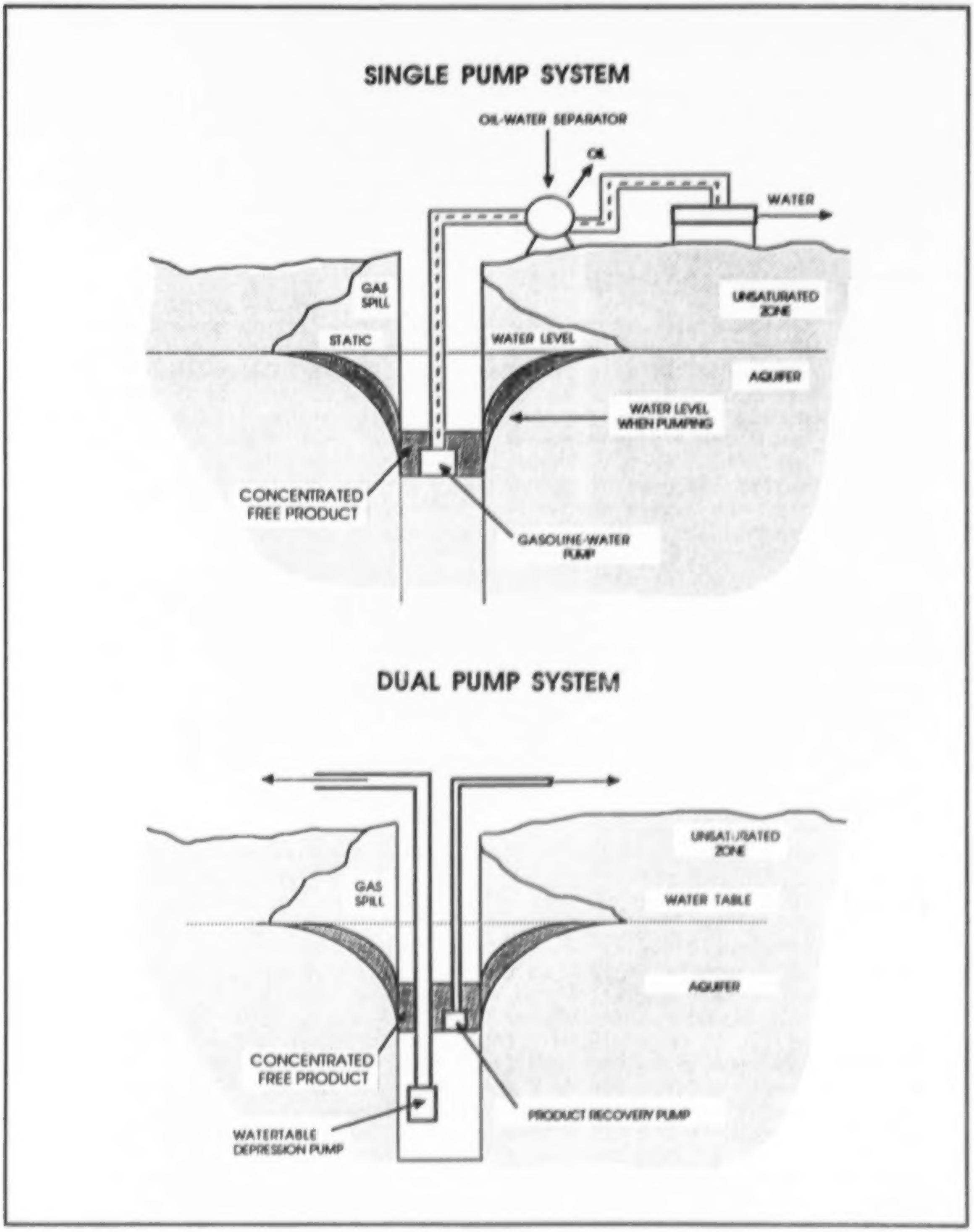

SINGLE PUMP SYSTEM
OIL-WATER SEPARATOR
OIL
WATER
GAS SPILL
UNSATURATED ZONE
STATIC
WATER LEVEL
AQUIFER
WATER LEVEL WHEN PUMPING
CONCENTRATED FREE PRODUCT
GASOLINE-WATER PUMP
DUAL PUMP SYSTEM
UNSATURATED ZONE
GAS SPILL
WATER TABLE
AQUIFER
CONCENTRATED FREE PRODUCT
WATERTABLE DEPRESSION PUMP
PRODUCT RECOVERY PUMP

Figure 18. Single Pump and Dual Pump Gasoline Recovery Systems

NAPL is present. The costs associated with dual pumps are higher, however, particularly if multiple recovery wells are required.

Another important consideration when using dual pump recovery is that lowering of the water table causes increased soil contamination because the floating NAPL will fall with the water table. Removal of these contaminants after the water table has been restored to its normal level can be very difficult. A remediation plan for the soils above the water table will not address these contaminants unless the water table remains lowered.

Vacuum Extraction of Floating NAPL

Vacuum extraction, more commonly associated with treatment of the unsaturated zone, has been shown to be successful in removing floating NAPL as well. Data from the site of a large gasoline spill show that 50 gallons per day of product was recovered from a single well pumping 75 cfm of contaminated air (CDM, 1990). The floating product was located in a medium to coarse sand with a less permeable silty layer approximately 10 feet above the product. The silt layer acted to confine contaminant vapors and enhance the effectiveness of the system. One advantage to using this method is that the system can be readily designed to treat both floating NAPL and contaminants in the unsaturated zone if needed.

Vacuum extraction to recover floating NAPL is a specialized form of soil venting where natural volatilization of liquid contaminants is enhanced by inducing pressure gradients in the soil above the NAPL. As the NAPL floats on the water table some of the contaminant will transfer from the liquid phase to the vapor phase (volatilize). The rate of natural volatilization depends primarily on the vapor pressure of the contaminants and the volume of air spaces in the soils above the NAPL plume. Vacuum extraction enhances natural volatilization by removing the vapors from the soil and bringing them to the surface. This creates a disequilibrium between the liquid and vapor phases and allows volatilization to continue at a greater rate.

Figure 19 shows a schematic diagram of a typical vacuum extraction system designed to remove floating NAPL. The contaminant vapors are removed by way of extraction wells that are screened just above the floating NAPL plume. The number and placement of the network of wells depends on the areal extent of the NAPL plume and the type of formation at the site. A vacuum is applied to the wells and the vapors are drawn through the soil air spaces to the wells, where they are captured and brought to the surface. To further enhance recovery, positive-pressure air injection wells may be employed. These wells force uncontaminated air into the subsurface and serve both to direct the contaminated vapors to the extraction wells and to provide a renewed source of air which promotes further transfer from the liquid to the vapor phase. If properly placed, positive injection wells can act as a barrier to off-site migration of contaminant vapors. For example, if injection wells are placed between the plume and nearby homes, vapors can be prevented from migrating towards the homes.

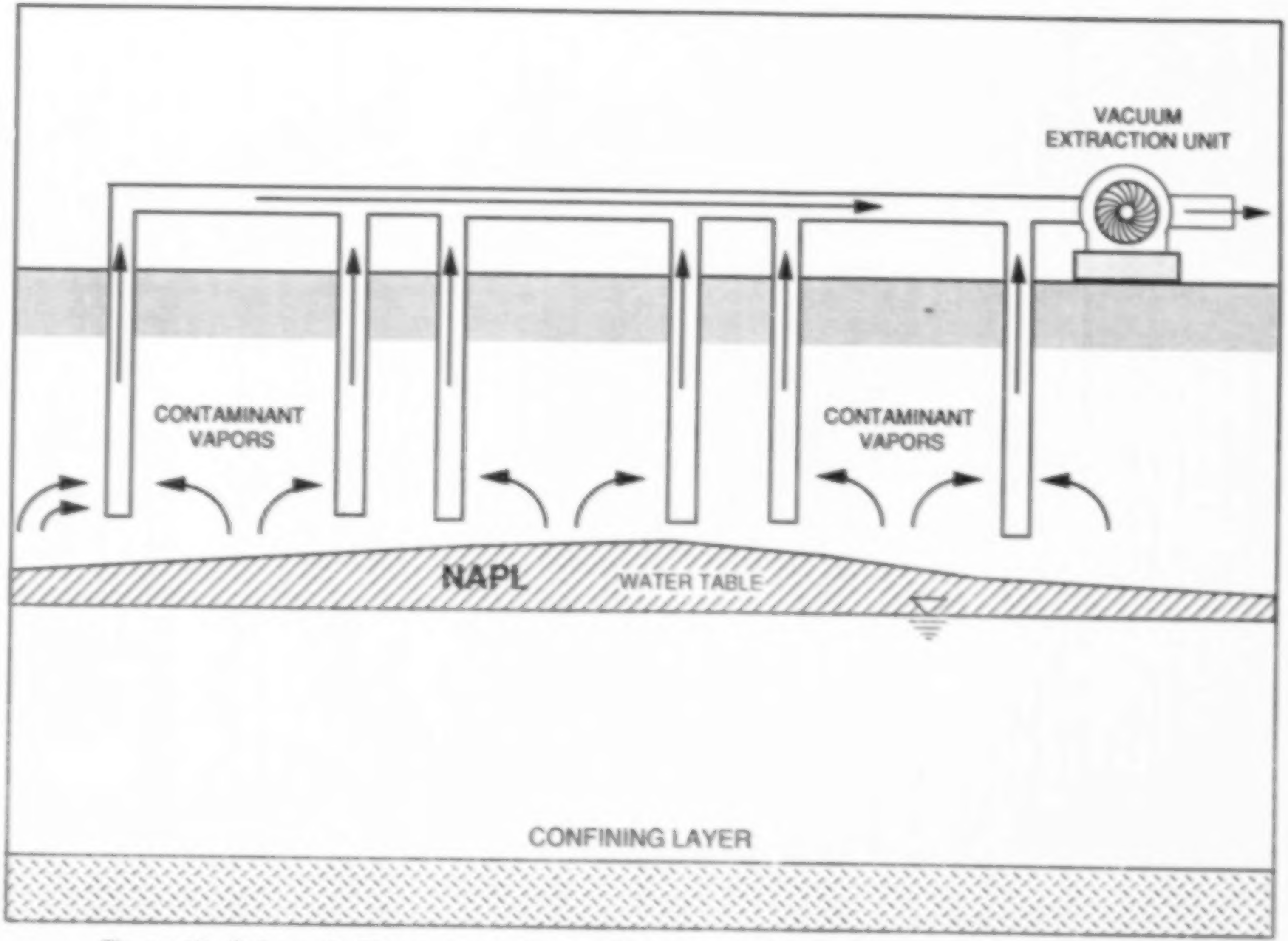

VACUUM
EXTRACTION UNIT
CONTAMINANT
VAPORS
CONTAMINANT
VAPORS
NAPL
WATER TABLE
CONFINING LAYER

Figure 19. Schematic Diagram of a Vacuum Extraction System for Recovering Floating NAPL

Vacuum extraction can be enhanced by: 1) placing an impermeable barrier (e.g., plastic sheets or clay soil) over the ground surface in the area being treated; and 2) depressing the groundwater table under the NAPL. The first action prevents short circuiting of the air flow; the second exposes more NAPL to the effects of the vacuum extraction system. A drawback to depressing the water table during vacuum extraction is that more soils get exposed to contamination. The contaminants that sorb to the newly exposed soils can be difficult and costly to remove.

Once brought to the surface, the contaminant-saturated vapors can be discharged to the atmosphere or treated to prevent air pollution. Vapors may require treatment prior to discharge to the atmosphere, depending on local air-discharge restrictions. If so, there are several treatment methods that can be used prior to discharge, including carbon adsorption and catalytic combustion.

Evaluating Vacuum Extraction

Table 14 lists CSFs for vacuum extraction and can be used as a worksheet to help evaluate this method at a particular site. Among the most important factors is the air conductivity of the soil. Coarse materials, such as sand and gravel, which tend to have greater air conductivity, are "more likely" to be amenable to vacuum extraction than fine-grained materials like clay or silt. Each of the remaining CSFs can be evaluated similarly to provide a preliminary screening of the suitability of vacuum extraction at the site of interest.

Soil temperature has two opposing effects on vacuum extraction. Contaminant volatility increases significantly with temperature, as evidenced by increases in contaminant vapor pressure with temperature. The air conductivity of the soil formation, however, will decrease with temperature due to decreases in air density and increases in air viscosity with temperature. The increased contaminant volatility will generally far outweigh the negative impacts of decreased air conductivity, and vacuum extraction can be expected to be more successful in areas where soil temperature is high. In some cases, air is heated prior to injection to raise the temperature of the soil and increase volatilization.

The water content of the formation also influences the effectiveness of vacuum extraction in two ways. First, a formation with a high water content will generally have a lower air conductivity than the same formation with a lower water content because it will have proportionately less air space. Second, pore water can absorb (dissolve) contaminants from the vapor phase, which serves to retard the removal of contaminant vapors. Dry soil is thus better suited to in-situ stripping than wet soil. However, the vacuum extraction process tends to dry out the soil over time, increasing the rate of removal.

The soil surface area and the organic content of the formation both influence the degree to which contaminants will be in the sorbed phase as opposed to the vapor phase. The greater the unit surface of a soil, the more likely contaminants will become sorbed to soil particles and the less effective vacuum extraction will be. Organic matter in the subsurface also serves to increase sorption of contaminants.

Table 14. Worksheet for Evaluating the Feasibility of Using Vacuum Extraction to Remove Floating NAPL at Your Site

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
SITE - RELATED					
* • Soil Air Conductivity	cm/sec		Low (<10^{-6}) ○	Medium (10^{-4} -10^{-6}) ○	High (>10^{-4}) ○
• Soil Temperature	°C		Low (<10) ○	Medium (10-20) ○	High (>20) ○
• Moisture Content	% volume		High (>30) ○	Medium (10-30) ○	Low (<10) ○
• Soil Surface Area	m^2/g		High (>1) ○	Medium (0.1-1) ○	Low (<0.1) ○
• Carbon Content	% weight		High (>10) ○	Medium (1-10) ○	Low (<1) ○
CONTAMINANT- RELATED					
* • Vapor Pressure	mm Hg		Low (<10) ○	Medium (10-100) ○	High (>100) ○
• Water Solubility	mg/L		High (>1000) ○	Medium (100-1000) ○	Low (<100) ○

OTHER CONSIDERATIONS

- Treatment of contaminant vapors may be required before discharge to atmosphere.

* CSFs denoted with an asterisk are typically more important than other CSFs

Two important contaminant-related CSFs are vapor pressure and water solubility. Compounds with higher vapor pressures will transform more readily from NAPL to the vapor phase and therefore are more easily removed by vacuum extraction. Compounds with low solubility generally have greater capacity to sorb to soil particles, and relatively insoluble compounds such as heavy fuel oils will not be as readily removed as more soluble products like gasoline.

Other considerations are less scientific in nature but can play a significant role in determining the applicability of vacuum extraction for removing floating NAPL. One advantage of this method over pumping wells is that a recovery system can be implemented without bringing groundwater to the surface. Extracted groundwater must generally be treated and/or disposed of. This will usually require special permitting which can delay implementation of the recovery system.

Relative Importance of CSFs

The two most important CSFs for vacuum extraction are the air conductivity of the soil and the vapor pressure of the contaminants. Together these two play the biggest role in determining the rate at which contaminants can be removed from the subsurface. Formations with low air conductivity require more extraction wells and/or increased suction at each well to attain the same removal rate as more highly conductive formations. Products such as heavy fuel oils that have low vapor pressures do not transfer from NAPL to the vapor phase as readily as lighter products such as gasoline, and will take longer to remove by vacuum extraction.

TREATMENT OF CONTAMINANTS DISSOLVED IN GROUNDWATER

Above-Ground Treatment

Above-ground treatment of groundwater is generally accomplished by installing extraction or recovery wells that bring the groundwater to the surface where it can be treated (i.e., pump and treat). The groundwater is then either disposed of or recharged to the subsurface. The two most commonly used above-ground treatment technologies are air stripping and carbon adsorption. These two are covered in detail in this section. Biological treatment of extracted groundwater shows promise of being effective, but has yet to be widely used or proven. Above-ground biological treatment is discussed in somewhat less detail in the New Technologies subsection.

Extraction of Groundwater

Each of the above-ground methods requires a groundwater extraction system to bring contaminated groundwater to the surface. Recovery of contaminants from the saturated zone using extraction methods can be difficult. Some of the difficulties inherent in an extraction system are presented prior to detailing each of the above-ground technologies.

As discussed in Section 2, contaminants can exist below the water table in three different phases: 1) dissolved; 2) sorbed; or 3) as NAPL. Dissolved contaminants can usually be removed fairly easily, particularly relative to the other two phases, which tend to persist in the saturated zone. However, the dissolved portion of total contaminant mass below the water table may be small. The effectiveness of a groundwater extraction system will often depend on the amount of sorbed or NAPL product below the water table and how readily these phases can be recovered.

As groundwater is extracted from the aquifer through a recovery well, the dissolved contaminants in permeable formations are readily mobilized. Dissolved contaminants in less permeable formations take longer to recover. Sorbed contaminants are not directly affected by pumping wells and can only be removed after going back into solution. As pumping continues, the dissolved concentrations of contaminant in the surrounding groundwater decrease, promoting dissolution of the sorbed contaminant, which can then be brought to the surface. NAPL trapped below the water table can also be difficult to remove. The interfacial tension forces between the soil particles and the NAPL are often large enough to inhibit mobilization, even in the presence of large hydraulic gradients. In such cases, dissolution of the NAPL to the dissolved phase over time will govern the extraction rate of the NAPL. Figure 20 shows dissolved contaminants being extracted by a recovery well over time. At time T1, pumping has just recently been started and the dissolved contaminants are fairly evenly dispersed throughout the aquifer. At time T2, dissolved contaminants in the more permeable sand and gravel have been largely removed, but the low permeability clay lenses continue to slowly release dissolved contaminants.

If significant amounts of NAPL and sorbed product exist in the saturated zone, the time-frame for remediation can be very long using groundwater extraction techniques, often spanning decades. The volume of groundwater withdrawn over this period can become very large. Unless injection wells are used to supply the clean water, which is rarely the case, this approach may utilize a considerable volume of uncontaminated groundwater surrounding the site to flush the contaminants from the polluted area (Mackay and Cherry, 1989). All the water recovered in the system must be treated, including the previously uncontaminated groundwater.

Figure 20 also illustrates the importance of follow-up monitoring at a site. Over time, the contaminant levels throughout much of the site may be very low and monitoring wells will probably reflect this. If treatment is discontinued, however, sorbed contaminants and immobilized NAPL will continue to dissolve into the groundwater. Unless monitoring continues well after remediation appears complete, the remaining pollutants will go undetected.

Air Stripping

Air stripping is the generic term used to describe several similar above-ground methods for treating contaminated groundwater. It is one of the most common methods used to remove volatile organic compounds from groundwater in the United States. The widespread use of air stripping is due to its proven success, its cost-effectiveness, and the fact that the concepts behind air stripping are well understood and design of the system is fairly straightforward.

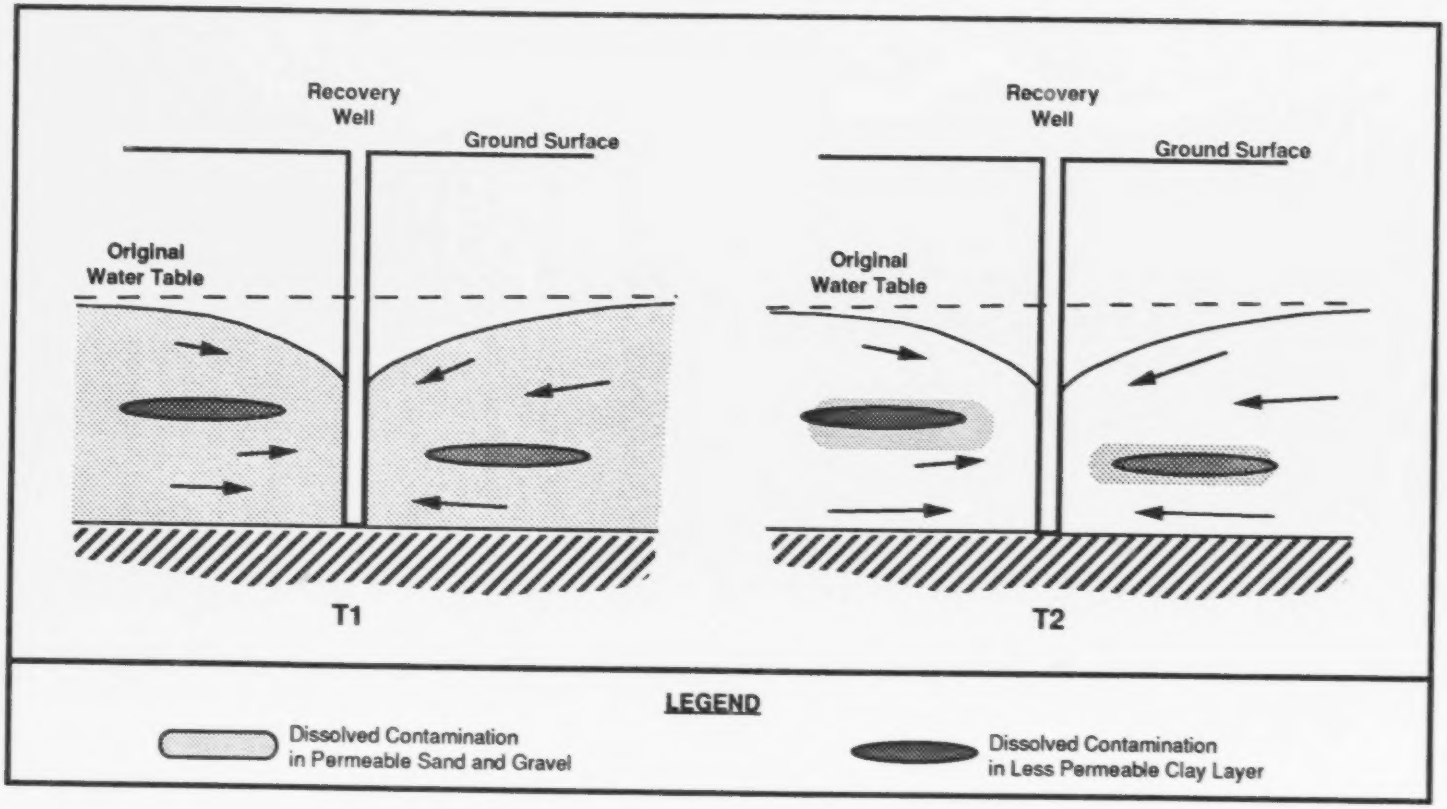

Recovery
Well
Ground Surface
Original
Water Table
T1
Recovery
Well
Ground Surface
Original
Water Table
T2
LEGEND
Dissolved Contamination
in Permeable Sand and Gravel
Dissolved Contamination
in Less Permeable Clay Layer

Figure 20. Retention of Dissolved Contaminants In Less Permeable Formations During Groundwater Extraction Treatment

Air stripping removes contaminants from groundwater through a controlled disequilibrium designed to promote the transfer of contaminants from the dissolved phase to the vapor phase. This is accomplished for all air stripping methods in two basic ways: 1) the surface area of the contaminated groundwater is increased, thus increasing the opportunity for volatilization; and 2) disequilibrium between the liquid and gaseous phases is maintained by replenishing the supply of "clean" air to the system through either natural or induced means.

There are four common air stripping methods: 1) diffused aeration, 2) tray aeration, 3) spray aeration, and 4) packed towers. Of these, packed towers are most commonly used to remove petroleum hydrocarbons from groundwater because of their great cost-effectiveness. The main components of each are described below.

Diffused Aeration - In diffused aeration, the contaminated groundwater is channeled through a large holding tank or pond with one or more diffuser pipes along the bottom. Air is pumped through the diffuser pipes and bubbles up through the tank, providing a medium into which the dissolved contaminant can volatilize. Once the air reaches the water surface it can be vented to the atmosphere or collected and treated.

The efficiency of diffused aeration can be increased by decreasing the bubble size, increasing the air to water ratio, agitating the water, or increasing the depth of water in the tank if the air bubbles are not saturated with contaminants when exiting the tank. Removal rates for diffused aeration range from 70 to 90 percent for many VOCs, which is often not an adequate removal efficiency at petroleum release sites.

Tray Aeration - Tray aeration is not as efficient in removing volatile organics as other air stripping methods presented in this section, but because of its simplicity and low maintenance, it is sometimes used as a pre-treatment for other methods. A typical tray aeration tank contains staggered slat trays. Water is fed into the top of the tank and flows by gravity through a distribution network onto the the trays. The trays disperse the water, increasing the water surface area exposed to the atmosphere. A blower can be installed at the base of the unit to increase the rate at which "clean" air is introduced to the system. As the air passes up through the unit, contaminant vapors are accumulated and eventually vented to the atmosphere or collected and treated.

Spray Aeration - In this method, contaminated groundwater is sprayed through nozzles over a pond or basin, greatly increasing the surface area of the water. As the water falls back to the pond, VOCs are transferred to the atmosphere. Because the contaminated groundwater system is exposed to the atmosphere, there is a constant source of "clean" air for stripping. However, it is difficult to contain and treat the contaminated air if this is desired or required. Other drawbacks include the relatively large land areas needed for the spray ponds and possible transport of contaminants to neighboring areas from mists created during spraying.

In addition to being used as a primary means of removing VOCs from groundwater, spray aeration has also been used to recharge the aquifer while at the same time providing additional removal of contaminants. This is done by spraying the effluent water from the treatment unit over the recharge area of the aquifer. The effluent not only percolates through the soil to the underlying aquifer but also undergoes additional contaminant removal.

Packed Towers - Of the air stripping methods, packed towers work best at removing volatile organic compounds (VOCs) from groundwater and they are often the most cost-effective method as well. For these reasons, packed towers are the most widely used air stripping method.

The tower, which can be more than 100 feet high, consists of a cylindrical column containing a packing material specially designed and arranged to increase the surface area of the groundwater being passed through it. Figure 21 shows a typical packed tower. Contaminated groundwater is pumped to the top of the column and allowed to flow by gravity down through the packing material while uncontaminated air is pumped up through the column. This produces a high air to water ratio and results in high removal efficiency. Packed towers can be designed to remove 90 to 99 percent of many VOCs from groundwater.

The design of packed towers is well understood relative to other treatment technology designs. Various design parameters can be adjusted to meet the requirements at a given site. The air to water ratio is one of the important design parameter and is chosen on the basis of cost-effectiveness and the Henry's law constant of the design contaminant (EPA, 1988b). A higher ratio will increase operating costs but will allow a decrease in the size of the tower, which can be quite large. Typical air to water ratios range from 20:1 to 100:1.

Evaluating Air Stripping

The worksheet of Table 15 can be used to help evaluate the likely effectiveness of air stripping at a particular site. The importance of each of the CSFs is discussed below.

Air stripping becomes more cost-effective relative to other technologies as the volume of groundwater to be treated increases. The amount released and the time since release both influence how much dissolved contamination there will be at a given site. A greater volume of contaminated groundwater is more likely for larger, older releases than smaller, more recent releases. The fact that air strippers can effectively treat large volumes of groundwater makes this technology especially attractive when large pumping rates are required to contain the dissolved plume.

Groundwater temperature affects air stripping performance, primarily because vapor pressure and temperature are related. Vapor pressure increases with temperature, and higher temperatures allow better removal rates. The impact of temperature on air stripping is most relevant in colder regions where winter removal rates may be significantly lower than summer rates unless system modifications are made. The presence of high concentrations of iron and manganese in groundwater retards hydrocarbon removal because they can precipitate onto the packing materials in the stripper. High total suspended solids concentrations are often an

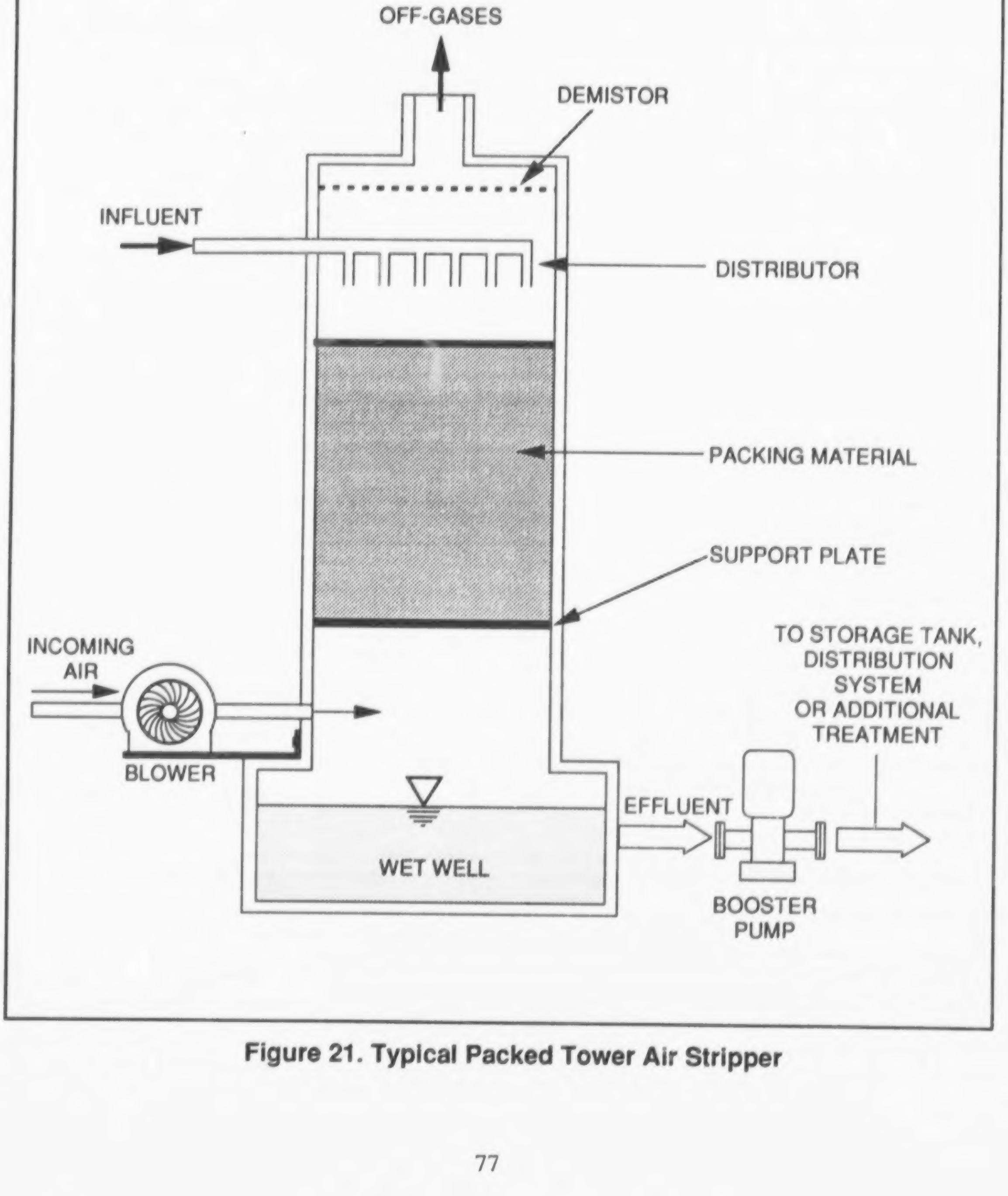

OFF-GASES
DEMISTOR
INFLUENT
DISTRIBUTOR
PACKING MATERIAL
SUPPORT PLATE
INCOMING AIR
BLOWER
TO STORAGE TANK, DISTRIBUTION SYSTEM OR ADDITIONAL TREATMENT
EFFLUENT
WET WELL
BOOSTER PUMP

Figure 21. Typical Packed Tower Air Stripper

Table 15. Worksheet for Evaluating the Feasibility of Using Air Stripping to Treat Extracted Groundwater at Your Site

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
★ • Amount Released	gallons		High (<1,000) ○	Medium (1,000-50,000) ○	Large (>50,000) ○
★ • Time Since Release	months		Short (<1) ○	Medium (1-12) ○	Long (>12) ○
SITE - RELATED					
• Groundwater Temperature	°C		Low (<10) ○	Medium (10-20) ○	High (>20) ○
• Total Suspended Solids Content of GW	mg/L		High (>20) ○	Medium (5-20) ○	Low (<5) ○
• Total Dissolved Iron and Manganese Content of GW	mg/L		High (>5) ○	Medium (0.2-5) ○	Low (<0.2) ○
CONTAMINANT- RELATED					
★ • Vapor Pressure	mm Hg		Low (<10) ○	Medium (10-100) ○	High (>100) ○
★ • Water Solubility	mg/L		High (>1000) ○	Medium (100-1000) ○	Low (<100) ○
★ • Dissolved Contaminant Concentration	mg/L		Low (<1) ○	Medium (1-100) ○	High (>100) ○

OTHER CONSIDERATIONS

- Air stripping is not effective in removing contaminants to drinking water standards.
- Permitting requirements can delay implementation.
- Can cost effectively treat large volumes of groundwater.
- Treatment of contaminant vapors may be required before discharge to atmosphere.

★ CSFs denoted with an asterisk are typically more important than other CSFs indication of the presence of iron and manganese in groundwater. Pre-treatment to remove suspended solids can enhance air stripping effectiveness.

The vapor pressure and water solubility of the contaminants affect how well an air stripping system works. As vapor pressure increases, the ease with which the contaminants are removed from the groundwater increases. Solubility has the opposite effect. Highly soluble contaminants tend to remain in solution longer as they pass through the air stripper and are not as effectively removed as less soluble ones. The influent concentration of the contaminants also is an important consideration. Air strippers can effectively remove high concentrations of volatile hydrocarbons.

Other factors to consider are regulatory in nature. These include effluent standards and permitting requirements. State or local requirements for groundwater quality may dictate the degree of treatment required at a site. Air strippers are not as effective at removing contaminants to very low levels as some other treatment methods. Special permits may be required to dispose of treated groundwater or even to set up the treatment system. Many states also have air discharge requirements that will necessitate treating contaminant vapors. This is usually accomplished by collecting the vapors and passing them through a carbon filter.

Relative Importance of CSFs

Among the most important CSFs in Table 15 are the contaminant-related factors (vapor pressure, water solubility, and dissolved contaminant concentration). Each of these factors is important in determining the technical effectiveness of an air stripping facility. The release-related factors (amount released and time since release) are also important for estimating the relative cost-effectiveness of this technology. The site-related CSFs also influence air stripping, but the treatment process can be modified to reduce any negative impact these factors might have.

Activated Carbon Adsorption

Like air stripping, activated carbon is commonly used in the United States to remove VOCs from contaminated groundwater. One of the most desirable aspects of activated carbon adsorption as a treatment process is its ability to remove contaminants to very low levels. Quality of effluent from a properly designed carbon adsorption unit can be at or below drinking water standards.

The effectiveness of carbon as a treatment process is due to its ability to function as a adsorbent for molecules dissolved in water. This ability is largely due to carbon's large internal surface area. The actual surface area of commercially available activated carbon depends on the source of carbon and the manufacturer, but an average value is about 1,000 m^2/g.

Two forms of carbon are used to treat water; powdered activated carbon (PAC) and granular activated carbon (GAC). Powdered carbon is dispersed freely into the water and subsequently filtered out. It is commonly used as a polishing step in the treatment of drinking water but rarely for treatment of contaminated groundwater because it is not easily reused. Granular carbon is coarser than powdered carbon and is typically contained in a cylindrical unit. Contaminated water is passed through the unit until the adsorption capacity of the carbon is spent. The granular carbon can then be regenerated for future use. Because only the granular form of carbon is commonly used in treatment of contaminated groundwater, only GAC treatment is discussed in this manual.

Carbon adsorption is less cost-effective at treating large volumes of groundwater than some other technologies (e.g. air stripping) because of the relatively high cost of carbon. Typical surface loading rates through GAC cylinders are from 5 to 7 gpm/ft^2. The cylinders holding the GAC usually range from 4 to 12 feet in diameter. A 10-foot diameter tank could treat about 400 to 500 gpm of contaminated groundwater, but the volume of carbon required to maintain this flow rate could be prohibitively expensive.

Design of a GAC system is not as straightforward as for air stripping because of the complex interaction of the factors influencing removal efficiency. Since the effectiveness of a particular design cannot be accurately predicted, pilot studies, should be undertaken before installing a GAC system.

Evaluating Carbon Adsorption

Many factors contribute to the successful operation of a GAC system. The worksheet of Table 16 lists some of these factors and can help the user evaluate carbon adsorption as a groundwater treatment technology. Each of the factors of Table 16 are discussed below.

The amount released and the time since release can give a rough idea of the volume of contaminated groundwater that will be encountered at the site. The effectiveness of carbon adsorption decreases as the volume of water requiring treatment increases. A larger amount of dissolved contamination can be expected for larger releases than for small ones, given other conditions are the same. The more time that has elapsed since the released first occurred, the more dissolved contamination there will be and the more widely dispersed the dissolved plume will be. The total volume of contaminated groundwater is, therefore, likely to be greater for larger, older releases.

The influent contaminant concentration should be considered when evaluating this method. GAC is extremely effective at removing very low levels of contamination, but if the total organic carbon (TOC) content of the contaminated groundwater is high, frequent carbon changes will be required. This can add significantly to treatment costs, and sites with high TOC concentrations may be better suited to another technology.

Carbon adsorption works better when the suspended solids and dissolved iron and manganese content of the groundwater are low. High concentrations (5 mg/L or more) of total iron and manganese may precipitate onto the carbon surface inhibiting the adsorption process. Excessive

Table 16. Worksheet for Evaluating the Feasibility of Using Carbon Adsorption to Treat Extracted Groundwater at Your Site

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
• **Amount Released**	gallons		Large (>50,000) ○	Medium (1,000-50,000) ○	Small (<1,000) ○
• **Time Since Release**	months		Long (>12) ○	Medium (1-12) ○	Short (<1) ○
SITE - RELATED					
* • **TOC Content of GW**	mg/L		High (>5) ○	Medium (1-5) ○	Low (<1) ○
• **Suspended Solids Content of GW**	mg/L		High (>20) ○	Medium (5-20) ○	Low (<5) ○
• **Total Dissolved Iron and Manganese Content of GW**	mg/L		High (>5) ○	Medium (0.2-5) ○	Low (<0.2) ○
CONTAMINANT- RELATED					
* • **Water Solubility**	mg/L		High (>1000) ○	Medium (100-1000) ○	Low (<100) ○
* • **Molecular Weight**	g/mole		Low (<100) ○	Medium (100-200) ○	High (>200) ○

OTHER CONSIDERATIONS

- Can remove contaminants to drinking water standards.
- Costs increase significantly if large volumes or highly contaminated groundwater is encountered.

* CSFs denoted with an asterisk are typically more important than other CSFs

suspended solids (greater than 20 mg/L) may have to be filtered out to prevent clogging of the carbon.

Highly soluble compounds are not as readily removed by GAC as less soluble ones. The more soluble compounds are more likely to stay in solution as the groundwater is passed through the GAC unit. Contaminants with high molecular weight are more readily adsorbed than lighter contaminants.

Relative Importance of CSFs

The most important factors are the TOC content of the groundwater, the water solubility of the contaminants, and the molecular weight of the contaminants. High TOC content would make carbon adsorption prohibitively expensive as the sole treatment process. Used in conjunction with a pre-treatment process, however, carbon adsorption can be used at virtually any site if very low effluent standards are required. Water solubility and molecular weight of the contaminants are important in evaluating the technical performance of carbon adsorption. The dissolved and suspended solids content of groundwater can usually be made more amenable to carbon adsorption through pre-treatment and are less important than other CSFs.

In-situ Treatment

Biorestoration

Biorestoration relies on naturally occurring or genetically altered microorganisms to transform contaminants to less hazardous compounds. Biodegradation of contaminants is enhanced by the addition of oxygen and nutrients. Bacteria capable of biodegrading petroleum hydrocarbons are commonly found in subsurface soils and some natural breakdown of hydrocarbons released to the subsurface is likely to occur at all sites. However, without the addition of nutrients and oxygen, biodegradation usually occurs very slowly. This treatment method is not as widely used as air stripping or carbon adsorption to treat groundwater, but under the right conditions, biorestoration can be very cost-effective and its use is likely to grow in the future.

In-situ biorestoration differs from air stripping and carbon adsorption in two main ways: 1) the contaminated groundwater remains below ground during remediation; and 2) the contaminants are not merely separated from the groundwater but are transformed to less toxic or even harmless compounds. In-situ biorestoration can lessen the risk of exposure incurred when contaminants are brought to the surface. It may also lessen or eliminate the need to treat or otherwise dispose of the contaminants as may be required in separation techniques.

Biodegradation of hydrocarbons can occur aerobically (in the presence of oxygen) or anaerobically (without oxygen). It is widely accepted that aerobic processes are far more effective in biodegrading petroleum hydrocarbons than anaerobic processes, and therefore, the focus of discussion is on aerobic processes.

Under complete aerobic degradation, hydrocarbons are biotransformed to carbon dioxide, water and biomass rather than physically separated, as with other technologies. Under less than ideal conditions (i.e., inadequate oxygen supply, lack of nutrients, etc.), less complete degradation may take place resulting in only partial breakdown of the hydrocarbons. If conditions can be enhanced, more complete biodegradation can take place. The fact that biodegradation can transform a contaminant to a non-toxic or less-toxic end product is a major advantage this technique holds over other cleanup methods. The other techniques serve only to concentrate, disperse, or relocate the contaminants, and further treatment or handling is usually required.

Although the biorestoration method described here is in situ, above ground equipment is required. At a minimum, an above ground mixing tank is required to add nutrients and oxygen to the water being introduced to the unsaturated zone. In some cases, the nutrient and oxygen rich treatment solution is also seeded with microorganisms known to be able to degrade contaminants at the site. However, some scientists believe that such seeding is unnecessary because the required organisms are ubiquitous in the environment. The mixing tank is also used as temporary storage of recirculated water, where additional bacteria can be grown and the organic content of the water can be reduced. Oxygen and nutrients are usually supplied by adding nutrient-enhanced water through infiltration basins at the ground surface or through recharge wells. A pumping well can be installed to control local groundwater flow and recirculate treated groundwater to the subsurface. Figure 22 shows a typical biorestoration system.

Conventional methods introduce oxygen to the subsurface by direct aeration or by the addition of hydrogen peroxide which, upon decomposition, generates oxygen. A recent study (Major et al., 1988) suggests that natural biodegradation may also be enhanced through the addition of a nitrate solution to the subsurface, but this method remains unproven and is not detailed here. A brief discussion of enhanced biodegradation through nitrate addition is presented in the New Technologies subsection.

It is difficult to predict the amounts of oxygen and nutrients that must be added to obtain optimal biodegradation at a given site. If too few nutrients are added, remediation efforts may be incomplete. Excessive nutrient addition can result in biological growth that clogs the soil, decreasing hydraulic conductivity and obstructing further treatment. To increase the likelihood of a successful biorestoration program at a particular site, pilot studies using samples collected at the site should be conducted to determine the appropriate nutrient additives and the required application rate.

Evaluating Biorestoration

Table 17 lists the critical success factors for biorestoration. By comparing the parameters at the site of interest to those in this table, a general understanding can be obtained of the suitability of biorestoration at that site. A preponderance of CSFs that match the rightmost column would indicate that biorestoration is likely to be effective at that site.

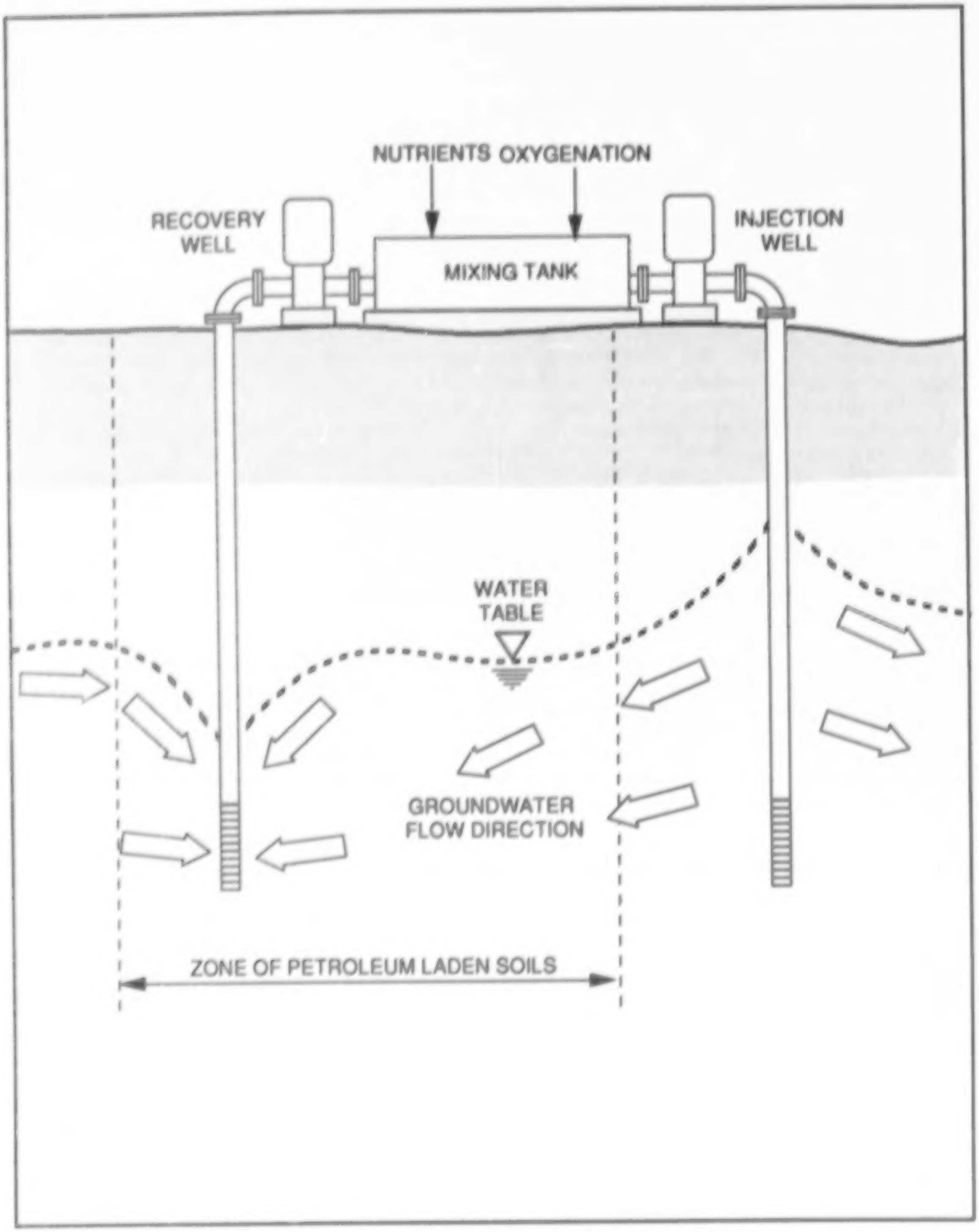

NUTRIENTS OXYGENATION
RECOVERY WELL
MIXING TANK
INJECTION WELL
WATER TABLE
GROUNDWATER FLOW DIRECTION
ZONE OF PETROLEUM LADEN SOILS

Figure 22. Typical In-Situ Biorestoration System

Table 17. Worksheet for Evaluating The Feasibility of Using Biorestoration to Treat Groundwater at Your Site

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE- RELATED					
• Time since release	months		Short (<1) ○	Medium (1-12) ○	Long (>12) ○
SITE- RELATED					
* • Hydraulic Conductivity	cm/sec		Low (<10^{-5}) ○	Medium (10^{-3} - 10^{-5}) ○	High (>10^{-3}) ○
* • Site Stratigraphy	-		Complex ○	-	Simple ○
• Groundwater temperature	°C		Low (<5) ○	Medium (5-10) ○	High (>10) ○
• pH	pH units		(< 6 or >8) ○	-	(6-8) ○
CONTAMINANT- RELATED					
• Biodegradability Refractory Index	-		Low (<0.01) ○	Medium (0.01-0.1) ○	High (>0.1) ○
• Total Organic Carbon Content of GW	mg/L		(<10 or >1000) ○	-	(10-1000) ○

OTHER CONSIDERATIONS

- It is difficult to monitor the effectiveness of the system
- Minimizes health risks by keeping contaminants below the ground surface.

* CSFs denoted with an asterisk are typically more important than other CSFs

Biorestoration is perhaps the only remedial technology for which a longer *time since release* can be an advantage. Because naturally-occurring microorganisms usually require time to acclimate, a biorestoration program initiated well after the time of release will often meet with more initial success than are started shortly after the release. This is particularly relevant for releases that are only discovered well after the release occurred.

A knowledge of the *hydraulic conductivity* of the soil, and the site hydrogeology in general, is extremely important in assessing the feasibility of biorestoration for a particular site. Even when all other factors are positive, *in-situ* biorestoration will not be successful if a low hydraulic conductivity prevents the added nutrients and oxygen from contacting the zone of contamination.

If the *site stratigraphy* is simple and fairly homogeneous, exposing the dissolved contaminants to oxygen and nutrients will be relatively easy. At more complex sites where groundwater flow patterns are difficult to predict, this technology will likely meet with less success.

Slightly alkaline *soil pH* is optimal for biodegradation, but anything in the range of 6.0-8.0 is considered acceptable. Most soils are slightly acidic and neutralization may be required at some sites. The *temperature* of the soil environment will also affect the rate of degradation. Warmer temperatures generally result in higher rates of degradation. While biodegradation has been shown to occur over a wide temperature range, the range of 20-35°C seems optimal but is typically above the normal subsurface temperature range. Also, microbes generally have a low tolerance for severe temperature changes as are experienced in northern regions.

The susceptibility of a given contaminant to biodegradation is an important consideration. Some compounds are much more readily biodegraded than others. Although it is not possible to predict with certainty whether a certain compound will be degraded at a specific site, the *refractory index* (RI) indicates a compound's susceptibility to degradation. The RI, a ratio of the BOD_5 (biochemical oxygen demand) to the COD (chemical oxygen demand), predicts the likelihood of biodegradation for a compound (Lyman *et al.*, 1982).

The *concentration of contaminant* dissolved in water affects biodegradation. If too low, bacteria may favor another competing food source; if too high, the contaminant may be toxic to the bacterial population. Aerobic bacteria are classically used for organic concentrations between 50 and 4,000 mg/L (Nyer, 1985). For *in-situ* treatment, organic concentrations as low as 10 mg/L may be sufficient. Dissolved petroleum hydrocarbons are unlikely to be found at concentrations as high as 4,000 mg/L.

Relative Importance of CSFs

Of the CSFs listed in Table 17, hydraulic conductivity and site stratigraphy are probably the most important. The success of this method depends on delivering nutrients and oxygen to the contaminants. Complex stratigraphy and/or poorly conductive formations prohibit this transport.

The biodegradability of the contaminants is also important, but the water soluble fraction of most petroleum products is comprised mostly of aromatic hydrocarbons, which have been shown to be fairly degradable in natural settings.

NEW TECHNOLOGIES

The treatment technologies previously discussed in this manual are only a portion of all available technologies, but they represent the most well understood and commonly used technologies. Other technologies show signs of being successful alternatives to the above-mentioned technologies. A few of these are described briefly below.

Biorestoration with Nitrate Addition

A recent study (Major et al., 1988) indicates that biodegradation of petroleum hydrocarbons may be effectively promoted by the addition of nitrate rather than oxygen. The laboratory study suggests that denitrification by subsurface microorganisms, where nitrate is reduced to nitrogen and oxygen, creates an environment suitable for biodegradation of the BTEX compounds (benzene, toluene, ethylbenzene and the xylenes). This process may be as effective as more conventional in-situ approaches that rely on the addition of nutrients and oxygen. However, it is difficult to equate laboratory success with field success due to the unique conditions found at each site.

If successful, nitrate addition could have significant advantages over conventional biodegradation techniques. Because nitrate is highly soluble, distribution of nitrate throughout the contaminated aquifer is easier than distribution of oxygen through either air sparging or hydrogen peroxide addition. Also, because the dosages can be relatively concentrated, fewer applications may be required, reducing the length and cost of remediation.

Air Sparging

Air sparging is a relatively inexpensive treatment technology developed, and primarily used, in Europe. There is no indication that this technology is currently being used in the United States and very little literature on air sparging is available in this country. Air sparging differs from the other saturated zone technologies presented in this manual in that it must be used in combination with treatment of soils in the unsaturated zone. The method involves using a vacuum extraction system to remove contaminant vapors from the unsaturated zone (soil venting) and pumping compressed air into the saturated zone to volatilize and mobilize contaminants dissolved in the groundwater.

Air sparging to remove contaminants from the saturated zone can be likened to in-situ air stripping. As in the more common above-ground air stripping techniques, sparging involves exposing contaminated groundwater to "clean" air which facilitates the volatilization of the contaminants from the groundwater. An injection well is installed in the region of greatest contamination, with the well screen located below the contaminant plume. Compressed air is pumped into the aquifer through the injection wells. The resultant air bubbles percolate up through the groundwater and are exposed to contaminants. Because no free air initially exists in the saturated zone, disequilibrium exists between the vapor and the dissolved phases of the contaminants. Contaminants in the dissolved phase will volatilize into the air bubbles until equilibrium is reached. Eventually the contaminant laden air bubbles reach the unsaturated zone and are captured through vacuum extraction.

Above-Ground Biological Treatment

Biological treatment of wastewater has proven quite cost-effective and it is the most widely used method of treatment for industrial and municipal wastewaters (Nyer, 1985). Above-ground biological treatment of contaminated groundwater is not as common, but could prove to be a successful alternative to other above-ground treatment technologies. The main restrictions to its use are: 1) the fact that the system must be run 24 hours a day; 2) start up of the system can take weeks to months; and 3) conventional biological reactors are not designed for the relatively low total organics concentrations found in contaminated groundwater. Research into applying above-ground biological methods to treat groundwater is ongoing, and may provide an effective means of remediation under the right conditions.

TECHNOLOGY COMPATIBILITY

Saturated Zone Technologies

The worksheets of this section can be used to evaluate the likely effectiveness of a single technology at a given site. However, clean up of the saturated zone can often be enhanced by using more than one technology. If the user finds that none of the technologies in the manual adequately address remediation goals, combining technologies may prove helpful. Below are examples of promising technology combinations.

- Removal of Floating NAPL - An increasingly common concern when using pumping wells to contain and recover floating NAPL is increased soil contamination due to lowering of the water table. Pumping wells are often required at a site, particularly if dissolved contamination is significant. Still, smearing of uncontaminated soil by floating NAPL can be minimized if trenches or vacuum extraction is initially used to recover as much NAPL as is practical before pumping wells are installed and the water table lowered.

- Treating Contaminated Groundwater - Air stripping and carbon adsorption are very compatible at sites where groundwater contamination is extensive and a high level of treatment is required. In such a case, neither of the technologies would likely be adequate by themselves. Air stripping can effectively treat large volumes of groundwater, but is not usually capable of removal to the low ppb range. Carbon adsorption is best suited for removing low-level contamination to near the drinking water standards. A combination of air stripping as a pre-treatment and carbon adsorption as a finishing process can be very effective.

Saturated and Unsaturated Zone Technologies

This manual focuses on remediation of the saturated zone (and excludes the unsaturated zone), but clean up of the saturated and unsaturated zones should not be considered as distinct activities. To have an effective overall remediation plan, the potential impact that clean up in one zone has on another should be considered. Some technologies used to treat these two zones are more compatible than others. For example, biorestoration of the saturated and unsaturated zones may be quite feasible, but vacuum extraction of floating NAPL would be inhibited by soil flushing in the unsaturated zone.

Table 18 shows the degree of compatibility between the more well known unsaturated zone and saturated zone technologies. Each of the saturated zone technologies in Table 18 are covered in this manual. The unsaturated zone technologies are not covered here but can be found in other literature including the companion document to this manual (EPA, 1989). Each of the boxes corresponding to an unsaturated zone/saturated zone technology combination shows the degree of compatibility between the two. The "very compatible" descriptor is attributed to two technologies that tend to enhance remediation of one or the other, while "not compatible" technologies retard the effectiveness of one or both. This table can be used to help in planning an effective remediation program that has short term goals and activities that are compatible with planned future activities.

TABLE 18. COMPATIBILITY OF SATURATED ZONE TECHNOLOGIES WITH UNSATURATED TECHNOLOGIES

SATURATED ZONE TECHNOLOGIES

UNSATURATED ZONE TECHNOLOGIES	Groundwater Extraction Methods	Vacuum Extraction of Floating NAPL	In-Situ Biorestoration
Vacuum Extraction	COMPATIBLE + Lowering of groundwater with recovery wells can increase influence of vacuum extraction - Lowered water table may cause increased sorbed phase.	VERY COMPATIBLE + One system can be designed for both unsaturated and saturated zone treatment. - Little or no affect on dissolved contaminant in saturated zone.	SOMEWHAT COMPATIBLE - Introduction of nutrient rich water to subsurface could interfere with vacuum extraction.
Soil Flushing	VERY COMPATIBLE + Extracted GW can be used as flushing medium after treatment.	SOMEWHAT COMPATIBLE - Vacuum extraction of floating NAPL must likely be completed before soil washing begins.	COMPATIBLE + GW extracted from containment wells can be used to distribute nutrients as well as flush contaminants - Surfactants may not be useful if they inhibit biodegradation
In-Situ Biorestoration	COMPATIBLE + After treatment, extracted groundwater may be enhanced for biorestoration and re-introduced to saturated zone.	COMPATIBLE + Vacuum extraction may induce increased oxygen levels, promoting natural biodegradation in the unsaturated zone.	VERY COMPATIBLE + One system can be designed to add nutrients to both the saturated and unsaturated zones.
Excavation	SOMEWHAT COMPATIBLE + Both can be implemented without impeding the performance of either.	SOMEWHAT COMPATIBLE - Excavation activities could interfere with vacuum extraction.	COMPATIBLE + Both can be implemented without impeding the performance of either.

SECTION 4

FOLLOW-UP MEASURES

RE-EVALUATE REMEDIATION GOALS

Remediation of petroleum product releases is often a long process. Initially, immediate goals will be set and addressed. Over time, the initial goals may be altered as new information becomes available and new goals added as different stages of the project are reached. For each new activity, alternative solutions should be evaluated. The basic method outlined in this manual for quickly evaluating alternative technologies can also be used in these later stages of remediation (as shown in Figure 3). For example, the initial goal of remediation may be to prevent dissolved contaminants from moving off site. A containment system may be installed which recirculates (as opposed to treats) the groundwater. A later goal may be to treat the groundwater before recirculation or disposal. The user could use the manual to quickly screen the technologies applicable to recovery or removal of contaminants dissolved in groundwater.

MONITORING TECHNICAL PERFORMANCE

Remediation is generally both lengthy and costly, and monitoring is the only way to determine whether the program is working. Proper monitoring can detect problems in the design or implementation of the selected technology that may be correctable with little added effort. The earlier such problems are detected, the more time and money will be saved. For example, a containment system should always be accompanied by a well-designed monitoring program to ensure that the entire plume is contained. If monitoring wells are not well placed, further migration of the plume could go undetected. This could result in the need for increased pumping rates or additional containment wells once the continued migration is discovered.

The performance of the treatment system should be continually evaluated to ensure that it is operating effectively. If a technology is performing poorly, it may be due to an improper design arising from an incomplete site assessment. It may be necessary to re-examine the data that were collected for the site assessment (see Figure 3) and collect more data to enhance the site assessment. Design modifications may be warranted if the understanding of site conditions changes appreciably.

Monitoring Well Networks

Regardless of the type of remediation program chosen, monitoring contamination in the saturated zone will always require monitoring wells to track performance or detect contaminant movement. The following are some of the points to consider in setting up a monitoring well network at a site.

- At least one well should be placed up-gradient of the site to detect background contamination levels. It is important to make sure the well is out of the zone of contamination produced by the release so that accurate background levels are obtained. It is also important that comparisons are made between background and contaminated samples taken from the same depth in the aquifer. If more than one aquifer is being sampled, up-gradient background levels should be taken for each aquifer.

- There should be enough down-gradient wells to adequately monitor the horizontal and vertical extent of contamination. In general, more wells are needed when complex stratigraphy or fluctuating water tables are encountered.

- All pathways for potential migration of contaminants should be monitored. For example, if multiple aquifers exist at a site, every aquifer that might potentially be contaminated through interaquifer exchange should be monitored.

- Wells should be screened at the appropriate depths. Wells should be screened at or near the water table for lighter than water contaminants and near the bottom of the aquifer for denser than water contaminants.

- The length of well screens should be considered. Longer screens are more likely to intercept the contaminant plume, but may result in diluted samples which do not reflect actual contaminant concentrations. Shorter screens give better concentration estimates but must be accurately located to ensure the plume is intercepted. Fluctuating water tables must also be considered and longer screens used if necessary to ensure the water table does not drop below the screen.

- Samples from pumping wells are generally diluted. They can provide useful information about the overall level of clean up achieved. However, monitoring well samples should also be taken to determine actual contaminant concentrations at specific locations in the subsurface.

- When determining water table contours, comparison of data should be made only between wells screened at the same vertical location in the same formation.

Measuring the Effectiveness of a Containment System

Delineating a pumping well's ZOC and taking water level measurements at the site are helpful in predicting whether floating NAPL or dissolved contaminants have been contained. However, sampling of wells is required to detect contaminants that may be escaping the capture zone.

The distribution of monitoring wells and the vertical location of screens on the wells is very important. Some of the wells must be outside the known limit of contamination in order to verify that migration has been prevented. The wells should also be screened based on the contaminant properties. To detect floating NAPL, well screens should be at the water table. If the contaminant is very dense, well screens should be near the bottom of the aquifer.

Criteria Used to Measure Removal Progress

Measuring the progress of floating NAPL removal is usually accomplished simply by comparing the volume of NAPL removed to an estimate of the total floating NAPL. Measuring removal progress for dissolved or sorbed contaminant is more difficult. Design of a treatment technology to remove dissolved or sorbed contamination is generally based on one or more constituents of concern rather than the petroleum product mixture. The constituent used in design is chosen based on its potential threat to the surrounding environment. Performance is then evaluated by measuring the concentrations of each contaminant of concern, and comparing those levels to clean-up goals.

Benzene, toluene, ethylbenzene and xylene (BTEX) are typically used for design criteria and performance monitoring of dissolved and sorbed contaminants in the saturated zone. These chemicals are aromatics and make up a significant portion of petroleum products (as much as 20% by weight in gasoline). Based on present knowledge, the toxicity of the BTEX compounds is orders of magnitude greater than the other natural petroleum constituents. They are also typically more soluble and mobile than other constituents. Of the aromatics, benzene is of greatest concern since it is a known human carcinogen. Benzene is also one of the more soluble and volatile aromatics. It is almost always detected in the subsurface when an UST release occurs. When measuring vapors, it is common to monitor BTEX and the alkanes, total hydrocarbons (which includes all the aromatics) or total volatiles.

In addition to the BTEX compounds, there are many different additives found in petroleum products, some of which can pose significant health risks. It may be desirable to use an additive for design criteria or performance monitoring, but only on a site by site basis after specific additives have been identified. Often there will be little evidence to suggest the additive does or does not present a health risk.

Relative contaminant concentrations change over time depending on their chemical properties, so it is possible that different contaminants will be used for design and for tracking performance at different stages of the clean-up. With time, aromatics dissolve in water (solubilize), evaporate into air (volatilize), and biodegrade until they cannot be detected. The contaminants likely to remain are more complex, less soluble, and less volatile than the aromatics. "More complex" constituents are constituents that have greater molecular weights and more complex molecular structures. These more complex molecules may break down into simpler molecules eventually. Constituents that are more complex than the simple aromatics (like BTEX) include certain additives like tetraethyl lead.

How to Measure Clean Up Progress

There are two basic measures of remediation progress in the saturated zone: 1) observed concentration levels in the subsurface; and 2) the percentage of contaminants removed to date from the subsurface. Clean up criteria are often set based on restoring groundwater quality to a some minimum level or removing some percentage of the total amount of contaminants released. These types of clean-up criteria are well suited to the above-mentioned progress measures.

Sampling and analyzing groundwater is the best way to determine whether significant amounts of contamination exist in the saturated zone. If clean-up criteria are based on a minimum contamination level, determining actual contamination levels in the groundwater is the only way to determine if the criteria have been met. A valuable tool to help evaluate remediation progress is to periodically sample at all monitoring wells. The data from these analyses can be used to create contour maps of contamination levels at the site. Over time, comparison of the contour maps can provide a time history of groundwater quality at the site.

Estimating the mass or volume of contaminants that have been removed from the subsurface is also a useful way to measure clean up progress at a site. This is especially true of recovery of NAPL, where concentration levels provide no useful information. The accuracy of this type of progress measure depends on the accuracy of the initial estimate of release volume and the accuracy of removal measurements. If the initial amount of released contaminants is unknown, the percentage of total clean up completed can not be determined. However, estimates of the amount of contaminants removed can still be useful as a means to monitor the performance of the technology.

Estimating the volume of contaminants released to the subsurface can be difficult. It is even more difficult to estimate how much contaminant has reached the saturated zone relative to the amount that attenuates in the unsaturated zone. Estimating the amount of contaminants removed during treatment is less difficult but often requires frequent and regular sampling. The common monitoring procedures used for measuring the mass of dissolved contaminants removed from groundwater for each of the treatment technologies is discussed briefly below.

- Air Stripping - In packed tower design, the tower is sized to handle a pre-determined flow rate and the contaminant removal efficiency can be fairly accurately determined by altering the design criteria. Influent and effluent concentrations can be taken periodically to ensure the desired removal rate is being maintained. To estimate the amount of contaminants removed from the subsurface, the average influent concentration can be multiplied by the removal rate to give the total contaminant mass removed.

- Carbon Adsorption - In this method, the effluent contaminant concentrations are generally monitored to determine when the carbon has used up its adsorption capacity and to ensure that effluent concentrations are meeting clean-up criteria. After "breakthrough" (the point when contaminant concentrations are detected in the effluent) the carbon is replaced.

Carbon adsorption removes virtually all targeted contamination from the groundwater if properly designed and maintained. To measure the mass of contaminant removed, the influent concentration must be monitored and the flow rate through the GAC unit known. Multiplying the two gives the mass removal rate of the system; and knowing the length of time the system has operated allows the total mass removed to date to be determined.

- Biorestoration - It is more difficult to determine how well this method is progressing through direct measurements than any of the other technologies. Indirect measures of biological activity are often substituted for direct measurements by determining carbon dioxide concentrations in the saturated zone (aerobic biodegradation produces carbon dioxide as one of its end products). A time-history of contaminant concentrations can also be made to help monitor treatment. It is important to regularly analyze the availability of oxygen, nutrients, pH, and microbial populations to make sure that conditions are suitable for biodegradation.

When is Remediation Complete?

Remediation of a site is complete when the clean-up goals and criteria are met and maintained. Just meeting the clean-up criteria is not sufficient reason to suspend remediation. Monitoring of the site should continue after the criteria appear to have been met because contamination levels can increase after treatment stops. The following are some of the causes of increased contamination levels at a site.

- Sorbed contaminants or contaminants in low permeability zones can persist in the subsurface, but may not be detected at monitoring wells while the system is operating. However, after shutdown these contaminants will tend to disperse causing future increases in contamination levels.

- Groundwater flow patterns created by recovery wells can dilute samples. After pumping stops, normal flow patterns return and concentration levels may increase.

- Cessation of pumping at a recovery well causes a rise in the water table. Contaminants sorbed to the soil may dissolve when contact with water is resumed, recontaminating the groundwater.

- Natural flushing by rainfall can cause contaminants trapped in the unsaturated zone to migrate to the saturated zone.

The decision to discontinue monitoring should be made jointly with regulatory officials and experienced professionals to ensure that remediation is complete.

REFERENCES

CH2M Hill. Evaluation of Ground-Water Extraction Remedies. Draft Project Summary Report 1989.

EPA. Estimation of the Public Health Risk from Exposure to Gasoline Vapor via the Gasoline Marketing System (draft), Office of Health and Environmental Assessment, Office of Air Quality Planning and Standards, Washington, DC. 1984.

EPA. A Compendium of Superfund Field Operations Methods. Washington, D.C. 1987a.

EPA. Ground Water. EPA/625/6-87/016. Cincinnati, OH. 1987b.

EPA. Strategies for Development of an UST Program Targeting Methodology. EPA Office of Underground Storage Tanks. Washington, D.C. 1987c.

EPA. Draft Internal Working Document Loci Research Report on Mobilization, Immobilization, and Transformation of Motor Fuel Constituents and Organic Chemicals in the Subsurface Environment. Prepared by PEI Associates Inc. for HWERL, ORD, Edison, NJ. 1988a.

EPA. Cleanup of Releases from Petroleum USTs: Selected Technologies. EPA/530/UST-88/001. USEPA. Office of Underground Storage Tanks. Prepared by Camp Dresser & McKee Inc. April 1988b.

EPA. Estimating Air Emissions From Petroleum UST Cleanups. U.S. EPA, Office of Underground Storage Tanks, Washington, D.C. 1989a.

EPA. Assessing UST Corrective Action Technologies. U.S. EPA, Washington, D.C. 1989b.

Farr, A.M., R.J. Houghtalen, and D.B. McWhorter. Volume Estimation of Light Nonaqueous Phase Liquids In Porous Media. Ground Water. Vol.28, No.1 1990

Freeze, R.A. and J.A. Cherry. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, NJ. 1979.

Geraghty, J.J. and D.W. Miller. Fundamentals of Ground Water Contamination, Short Course Notes. Geraghty and Miller Inc. 1985.

Ghassemi, M., A. Phanahloo, S. Quinlivan. Physical and Chemical Characteristics of Some Widely Used Petroleum Fuels: a Reference Data Base for Assessing Similarities and Differences between Synfuel and Petrofuel Products, Energy Sources, 1984, 7, pp. 377-401.

Hall, R., S.B. Blake, S.C. Champlin, Jr. Determination of Hydrocarbon Thickness in Sediments Using Borehole Data. Fourth National Symposium on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Columbus, OH. 1984.

Heath, R.C. Basic Ground-Water Hydrology. Water Supply Paper 2220. United States Geological Survey. 1983. pp. 71.

Hillel, Daniel. Fundamentals of Soil Physics. Harcourt Brace and Jovanovich, Publishers. New York. 1980.

Hoag, G. E., C.J. Bruell, M.C. Marley. A study of the Mechanisms Controlling Gasoline Hydrocarbon Partitioning and Transport in Groundwater Systems, University of Connecticut, Prepared for the United States Geological Survey, Reston, VA, 1984.

ICF, Inc. Petroleum Data Collection and Assessment of Risk Approach. Draft Report, 1984.

Javandel and Tsang. Capture Zone Type Curves: A Tool for Aquifer Cleanup. Ground Water, Vol.24, No.5. 1986.

Krishnayya, A.V., M.J. O'Connor, J.G. Agar and R.D. King. Vapour Extraction Systems: Factors Affecting Their Design and Performance. Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration. 1988.

Lyman, W.J., W.F. Reehl, and D.H. Rosenblatt. Handbook of Chemical Property Estimation Methods. McGraw-Hill Book Co. New York. 1982.

Mackay, D.M. and J.A. Cherry. Groundwater Contamination: Pump-and-treat remediation. Environmental Science and Technology. Vol.23, No.6. 1989.

Major, D.W., C.I. Mayfield, J.F. Barker. Biotransformation of Benzene by Denitrification in Aquifer Sand. Ground Water. 26(1): 8-14. 1988.

Nyer, E.K. Groundwater Treatment Technology. New York: Van Nostrand Rheinhold. 1985.

Schwarzenbach, R.P. and J. Westall. Transport of Nonpolar Organic Compounds from Surface Water to Groundwater. Laboratory Sorption Studies. Environmental Science and Technology. V 35. 1981

Smith, J.H., J.C. Harper, H. Jaber. Analysis and Environmental Fate of Air Force Distillate and High Density Fuels, Tyndall Air Force Base, Engineering and Services Laboratory. Florida. 1981.

Sutton, P.A. and J.F. Barker. Migration and Attenuation of Selected Organics in a Sandy Aquifer - A Natural Gradient Experiment. Ground Water. Vol.23, No.1. pp. 10-16. 1985

Testa, S.M. and M.T. Paczkowski. Volume Determination and Recoverability of Free Hydrocarbon. Ground Water Monitoring Review. Vol. 9, No. 1. 1989.

Thurman, E.M. Organic Geochemistry of Natural Waters. Kluwer Academic Publishers. 1985.

Todd, D.K. Ground Water Hydrology. Wiley & Sons, New York. 1980.

APPENDIX A

HOW TO USE THE WORKSHEETS

The examples provided herein demonstrate how to use the worksheets that are presented throughout the manual. Included with each example is a brief discussion of the completed worksheet and how it can be interpreted. A copy of each blank worksheet is provided at the back of the manual. These can be detached and copied for use in evaluating any number of release sites.

Site Setting - Each of the examples assumes that the release occurred in the same setting and under the same circumstances. Automotive gasoline is assumed to have leaked over an eight month period from an UST in the upper Midwest region of the United States. The site is in a rural area with no major developments in the immediate vicinity. The UST is in a silty sand formation about 200 feet thick and overlies sedimentary bedrock. The typical depth to water is about 10 meters (33 feet).

Listed in Table A-1 are all the CSFs required to complete the sample worksheets along with their assumed values and sources (e.g., tables or figures in the text, simple field tests, or other sources such as a local USGS office). Note that the contaminant-related CSFs have values for both the bulk liquid (gasoline) and a constituent of the bulk liquid (toluene). This is because the bulk liquid properties are appropriate for some of the worksheets while the constituent properties are appropriate for others. Toluene is used because it is commonly found in a variety of petroleum products and is relatively soluble (see discussion in Section 2). Which to target, bulk liquid or individual constituents, is discussed for each sample problem.

Table A-1. Assumed Data for Sample Problems

CSF	VALUE	SOURCE
RELEASE-RELATED		
Amount Released	12,000 gal	* estimated from Owner records
Rate of Release	Slow Leak	* estimated from Owner records
Time Since Release	8 months	* estimated from Owner records
SITE-RELATED		
Depth to Groundwater	10 meters	* from USGS records
Preferential Flow Pathways	Unknown	* site walkover
Hydraulic Conductivity	10^{-4} cm/sec	Table 3 (pg. 16)
Rainfall Infiltration Rate	0.1 cm/day	* from USGS records
Soil Temperature	7°C	Figure 4 (pg. 19)
Soil Surface Area	0.05 m^2/g	Table 4 (pg. 17)
Interfering Structures	Not Present	* local public works dept.
TOC Content of GW	3 mg/L	* groundwater sample
Suspended Solids Content	25 mg/L	* groundwater sample
Iron and Manganese Content	<0.2 mg/L	* groundwater sample
CONTAMINANT-RELATED		
Liquid Viscosity (gasoline)	0.45 cP	Table 7 (pg. 26)
Vapor Pressure (gasoline)	469 mm Hg	Table 7 (pg. 26)
Vapor Pressure (toluene)	21.8 mm Hg	Table 8 (pg. 27)
Water Solubility (gasoline)	158 mg/L	Table 7 (pg. 26)
Water Solubility (toluene)	537 mg/L	Table 8 (pg. 27)
Molecular Weight (toluene)	92.1 g/mole	many sources

---

* CSFs that have sources marked with an asterisk have been given assumed values which could have been obtained from the source shown.

Example 1 - Table 10 (pg. 35)
"Likelihood of NAPL being Present on the Water Table"

Table 10 from the manual has been completed using the data in Table A-1 and is included on the following page. Note that the properties of the bulk liquid rather than individual constituents should be used to determine values for CSFs in Table 10 (see Section 2 of the manual). A summary of the data in the completed worksheet is shown in Table A-2. The middle column shows the number of times, or frequency, that CSFs fall into each of the three likelihood categories. The right most column shows the frequency that CSFs identified as more important than others in the worksheet fall into each of the likelihood categories.

Table A-2

Likelihood	Frequency	No. of Relatively Important CSFs
Higher	3	2
Medium	6	2
Lower	3	1

The distribution of CSFs in the completed worksheet do not clearly indicate that NAPL would or would not be present on the water table. This is true of the more important CSFs as well as the CSFs in general, and further study of the CSFs is required to better interpret the results.

The "amount released" and "liquid viscosity" CSFs are in the high range and more important relative to some other CSFs. This suggests that a fairly large volume of relatively mobile petroleum product was released. The "depth to groundwater", "hydraulic conductivity", and "soil surface area" CSFs are in the medium range and suggest that bulk gasoline could move somewhat easily down through the unsaturated zone to the water table. This would be especially true if "preferential flow pathways" were discovered at the site during a more thorough investigation. However, the "rate of release" was slow, and NAPL will have had time to transform to other phases.

The worksheet indicates that, presently, some NAPL likely remains on the water table. Prior to this evaluation, a significant amount of the release probably reached the water table as NAPL. But, over time, a portion of the floating NAPL is likely to have dissolved, sorbed, or volatilized.

Table 10. Likelihood of NAPL Being Present on the Water Table

FACTOR	UNITS	SITE OF INTEREST ▼	INCREASING LIKELIHOOD →		
RELEASE- RELATED					
* • Amount Released	gal	12,000	Small (<1,000) ○	Medium (1000-10,000) ○	Large (>10,000) ●
* • Rate Of Release	-	Slow	Slow Release ●	- - ○	Instantaneous Release ○
• Time Since Release	months	8	Long (>12) ○	Medium (1-12) ●	Short (< 1) ○
SITE - RELATED					
* • Preferential Flow Pathways	-	Unknown	Not Present ○	Unknown ●	Present ○
* • Depth To Groundwater	meters	10	Deep (>15) ○	Medium (2-15) ●	Shallow (< 2) ○
• Hydraulic Conductivity (of the Unsaturated Zone)	cm/sec	10^{-4}	Low ($<10^{-5}$) ○	Medium (10^{-5}-10^{-3}) ●	High ($>10^{-3}$) ○
• Rainfall Infiltration Rate	cm/day	0.1	High (0.2) ○	Medium (0.05-0.2) ●	Low (<0.05) ○
• Soil Temperature	°C	7	Cool (<10) ●	Medium (10 - 20) ○	Warm (>20) ○
• Soil Sorption Capacity (Surface Area)	cm^2/g	0.05	High (>1) ○	Medium (0.1-1) ○	Low (<0.1) ●
CONTAMINANT- RELATED					
* • Liquid Viscosity	cP	0.45	High (>20) ○	Medium (2-20) ○	Low (<2) ●
• Vapor Pressure	mm Hg	469	High (>100) ●	Medium (10-100) ○	Low (<10) ○
• Water Solubility	mg/L	158	High (>1000) ○	Medium (100-1000) ●	Low (<100) ○

* CSFs denoted with an asterisk are typically more important than other CSFs

Example 2 - Table 11 (pg. 36)
"Likelihood of Dissolved Contaminants Being Present in the Saturated Zone"

Table 11 has been completed using the data in Table A-1 and is included on the following page. Bulk liquid properties are used in this example and are more appropriate than individual constituents for two main reasons: 1) the amount of dissolved contamination in the saturated zone depends to a large degree on the amount of bulk liquid that reaches the water table, which in turn is partially dependent on properties of the bulk liquid, and 2) the total amount of contaminant that will transform from a given amount of bulk liquid to the dissolved phase is related to the water solubility of the bulk liquid, not the solubilities of the individual constituents. A summary of the data in the completed worksheet is shown in Table A-3.

Table A-3

Likelihood	Frequency	No. of Relatively Important CSFs
Higher	4	2
Medium	6	3
Lower	2	0

Based on the worksheet results, it is likely that there is a significant amount of dissolved contamination in the saturated zone:

- only two of the 12 CSFs (soil temperature and vapor pressure) suggest a "lower likelihood" of dissolved contamination, and these are not among the more important of the CSFs in Table 11;
- the water solubility of gasoline is in the moderate range, but is high relative to other bulk petroleum products;
- the low liquid viscosity of the bulk liquid, the relatively large amount of product released, and the moderate depth to groundwater at the site suggest that a significant amount of NAPL could have reached the water table, where dissolution of the product is facilitated;
- a fairly long time has elapsed since the release first occurred, which would allow spreading of the NAPL plume and increased dissolution of product;
- infiltrating rain water has likely acted to flush contaminants trapped in the unsaturated zone down to the saturated zone in the dissolved phase; and
- the moderate fluctuations in the water table will increase contact area between NAPL and groundwater, furthering dissolution of NAPL.

Table 11. Likelihood of Dissolved Contaminants Being Present in the Saturated Zone

FACTOR	UNITS	SITE OF INTEREST ▼	INCREASING LIKELIHOOD →		
RELEASE- RELATED					
* • Amount Released	gal	12,000	Small (100) ○	Medium (100-1000) ○	Large (>1000) ●
* • Rate Of Release	-	Slow	Instantaneous Release ○	--	Slow Release ●
* • Time Since Release	months	8	Short (<1) ○	Medium (1-12) ●	Long (>12) ○
SITE - RELATED					
• Depth To Groundwater	meters	10	Deep (>15) ○	Medium (2-15) ●	Shallow (<2) ○
• Fluctuating Water Table	-	Moderate	Steady ○	Moderately Fluctuating ●	Highly Fluctuating ○
• Hydraulic Conductivity (of the Unsaturated Zone)	cm/sec	10^{-4}	Low ($<10^{-5}$) ○	Medium (10^{-5}-10^{-3}) ●	High ($>10^{-3}$) ○
* • Rainfall Infiltration Rate	cm/day	0.1	Low (<0.05) ○	Medium (0.05-0.2) ●	High (>0.2) ○
• Soil Temperature	°C	7	Cool (<10) ●	Medium (10-20) ○	Warm (>20) ○
• Soil Sorption Capacity (Surface Area)	m^2/g	0.05	High (>1) ○	Medium (0.1-1) ○	Low (>0.1) ●
CONTAMINANT- RELATED					
• Liquid Viscosity	cP	0.45	High (>20) ○	Medium (2-20) ○	Low (<2) ●
• Vapor Pressure	mm Hg	469	High (>100) ●	Medium (10-100) ○	Low (<10) ○
* • Water Solubility	mg/L	158	Low (<100) ○	Medium (100-1000) ●	High (>1000) ○

* CSFs denoted with an asterisk are typically more important than other CSFs

The overall conditions at the site are favorable for the presence of dissolved contamination, and a fairly large dissolved plume can be expected. As discussed in Section 2 of the manual, the dissolved plume will likely be comprised mostly of aromatic hydrocarbons, which make up a significant portion of the water soluble fraction of most petroleum products. Of the aromatic hydrocarbons, the BTEX compounds (benzene, toluene, ethylbenzene and the xylenes) are often a significant contributor to the water soluble fraction. One or more of the BTEX compounds are often targeted in groundwater monitoring programs and design of treatment systems.

Example 3 - Table 12 (pg. 58)
"Worksheet for Evaluating the Feasibility of Using Trench Excavation to Contain Floating NAPL"

Table 12 of the main text has been completed using the data in Table A-1 and is included on the following page. The properties of the bulk gasoline rather than individual constituents of gasoline are appropriate for evaluating containment of NAPL and are used in the completed worksheet. A summary of the results is shown in Table A-4.

Table A-4

Feasibility	Frequency	No. of Relatively Important CSFs
More Feasible	5	2
Somewhat Feasible	1	0
Less Feasible	1	1

At first glance, the distribution of CSFs in Table A-4 might suggest that trench excavation looked promising at this site. Five of the seven CSFs are in the "more feasible" category, including two identified in the worksheet as more important relative to some other CSFs. One CSF is in the "somewhat feasible" and one in the "less feasible" category. However, the depth to groundwater of 10 meters, the only "less feasible" parameter, is very important in evaluating this technology from a cost perspective. Digging and maintaining trenches to depths greater than about 5 meters below ground surface can be very costly. This factor could outweigh all other CSFs in the worksheet, even when they appear to be quite favorable.

A first pass evaluation of the completed worksheet indicates that another alternative (e.g. pumping wells) may be better suited to this site. But this does not rule out trench excavation altogether. A first pass evaluation of pumping wells at the site may show that technology to be no more feasible than trench excavation. If so, further information would be required before screening of containment technologies could be accomplished.

Table 12. Worksheet for Evaluating the Feasibility of Using Trench Excavation to Contain Floating NAPL

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
• Amount Released	gallons	12,000	Large (>500,000) ○	Medium (50,000-500,000) ○	Small (<50,000) ●
• Time Since Release	months	8	Long (>12) ○	Medium (1-12) ●	Short (<1) ○
SITE - RELATED					
* • Depth to Groundwater	meters	10	Deep (>5) ●	Medium (1-5) ○	Shallow (<1) ○
• Stability of Soil Formation	-	Stable	Unstable ○	-	Stable ●
* • Presence of Interfering Structures	-	None	Present ○	-	Not Present ●
CONTAMINANT- RELATED					
• Liquid Viscosity	cP	0.45	High (>2) ○	Medium (1-2) ○	Low (<1) ●
* • Liquid Density	g/cm^3	0.73	High (>1) ○	-	Low (<1) ●

OTHER CONSIDERATIONS

- Trench excavation can generally be implemented quickly.
- Costs for this method are typically lower than for other methods
- Denser than water contaminants cannot typically be contained with trench excavation

* CSFs denoted with an asterisk are typically more important than other CSFs

Example 4 - Table 16 (pg. 81)
"Worksheet for Evaluating the Feasibility of Using Carbon Adsorption to Treat Extracted Groundwater"

Table 16 has been completed using the data in Table A-1 and is included on the following page. The contaminants in the dissolved phase are of primary importance in evaluating carbon adsorption. Therefore, values for CSFs used in the completed worksheet are based on the properties of a constituent of gasoline (toluene) rather than properties of bulk gasoline (see Section 2). Other of the more soluble compounds in gasoline (e.g. benzene) could also be evaluated in the same manner as toluene. A summary of the results is shown in Table A-5.

Table A-5

Feasibility	Frequency	No. of Relatively Important CSFs
More Feasible	1	0
Somewhat Feasible	4	2
Less Feasible	2	1

The results of the worksheet suggest that carbon adsorption is not likely to be feasible as the primary treatment process at this site (at least for toluene):

- the amount of product released and the time elapsed since the release first occurred indicate that a moderately large volume of groundwater would require treatment. Treatment by carbon adsorption is generally more costly than other technologies and not suited to large volume clean ups;

- the water solubility and molecular weight CSFs indicate that carbon adsorption can remove toluene from the groundwater, but not as efficiently as heavier, less soluble compounds. This would result in more carbon use and/or a slower treatment rate;

- the total organic carbon (TOC) content of the groundwater is within a range treatable by carbon adsorption.

- the iron and manganese in the groundwater is favorable to carbon adsorption but the suspended solids content is high. However, filtering the groundwater prior to treatment should solve this problem.

A first pass evaluation of carbon adsorption at this site indicates that other technologies might be better suited to removing toluene from groundwater at the site. However, other factors not included on the

Table 16. Worksheet for Evaluating the Feasibility of Using Carbon Adsorption to Treat Extracted Groundwater at Your Site

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
• **Amount Released**	gallons	12,000	Large (>50,000) ○	Medium (1,000-50,000) ●	Small (<1,000) ○
• **Time Since Release**	months	8	Long (>12) ○	Medium (1-12) ●	Short (<1) ○
SITE - RELATED					
* • **TOC Content of GW**	mg/L	3	High (>5) ○	Medium (1-5) ●	Low (<1) ○
• **Suspended Solids Content of GW**	mg/L	25	High (>20) ●	Medium (5-20) ○	Low (<5) ○
• **Total Dissolved Iron and Manganese Content of GW**	mg/L	<0.2	High (>5) ○	Medium (0.2-5) ○	Low (<0.2) ●
CONTAMINANT- RELATED					
* • **Water Solubility**	mg/L	537	High (>1000) ○	Medium (100-1000) ●	Low (<100) ○
* • **Molecular Weight**	g/mole	92.1	Low (<100) ●	Medium (100-200) ○	High (>200) ○

OTHER CONSIDERATIONS

- Can remove contaminants to drinking water standards.
- Costs increase significantly if large volumes or highly contaminated groundwater is encountered.

* CSFs denoted with an asterisk are typically more important than other CSFs

worksheet, such as the level of treatment required, may make this alternative more attractive. For example, if the groundwater must be treated to drinking water standards, there are no proven alternatives to carbon adsorption. In such a case, the best course of action might be to pre-treat the groundwater using another technology and use carbon adsorption as a finishing process.

GLOSSARY OF TERMS

Absorption - the penetration of atoms, ions or molecules into the bulk mass of a substance.

Adsorption - the retention of atoms, ions or molecules onto the surface of another substance.

Aerobic - in the presence of oxygen.

Anaerobic - in the absence of oxygen.

Aquifer - a geologic formation capable of transmitting significant quantities of groundwater under normal hydraulic gradients.

Aquitard - a geologic formation that may contain groundwater but not capable of transmitting significant quantities of groundwater under normal hydraulic gradients.

Aromatic - of or relating to organic compounds that resemble benzene in chemical behavior.

Attenuation - to reduce or lessen in amount (e.g., a reduction in the amount of contaminants in a plume as it migrates from the source).

Biodegradation - a process by which microbial organisms transform or alter through enzymatic action the structure of chemicals introduced into the environment.

Biomass - The amount of living matter in a given area or volume.

Bulk Density - the amount of mass of a soil per unit volume of soil; where mass is measured after all water has been extracted and total volume includes the volume of the soil itself and the volume of air space between the soil grains.

Capillary Suction - process where water rises above the water table into the void spaces of a soil due to tension forces between the water and soil particles.

Capillary Fringe - The zone of a porous medium above the water table within which the porous medium is saturated but is at less than atmospheric pressure. The capillary fringe is considered to be part of the vadose zone, but not of the unsaturated zone.

Confined Aquifer - an aquifer under greater than atmospheric pressure, bounded above and below by relatively impermeable formations.

Confining Layer - a geologic formation exhibiting low permeability that inhibits the flow of water.

Consolidated Soil - when a soil is subjected to an increase in pressure due to loading at the ground surface, a re-adjustment in the soil structure occurs. The volume of space between the soil particles decreases and the soil tends to settle or consolidate over time.

Constituent - an essential part or component of a system or group: examples are an ingredient of a chemical system, or a component of an alloy.

Degradation Potential - the degree to which a substance is likely to be reduced to a simpler form by bacterial activity.

Dissolution - Dissolving of a material in a liquid solvent (e.g., water).

Downgradient - in the direction of decreasing static head.

Drawdown - lowering of the water table due to withdrawal of groundwater from a well.

Fluid Conductivity - the constant of proportionality in Darcy's Law relating the rate of flow of a fluid through a cross-section of porous medium in response to a hydraulic gradient. Fluid conductivity is a function of the intrinsic permeability of a porous medium and the kinematic viscosity of the fluid which flows through it. Fluid conductivity has units of length per time (cm/sec).

Free Product - a contaminant in the unweathered phase, where no dissolution or biodegradation has occurred.

Field Capacity - the percentage of water remaining in the soil 2 or 3 days after gravity drainage has ceased from saturated conditions.

Henry's Law - the relationship between the partial pressure of a compound and the equilibrium concentration in the liquid through a constant of proportionality known as Henry's Law Constant. See partial pressure.

Heterogeneous - varying in structure or composition and having different properties in different locations or directions.

Homogeneous - similar in structure or composition throughout and having similar properties in all locations and directions.

Hydraulic Conductivity - the constant of proportionality in Darcy's Law relating the rate of flow of water through a cross-section of porous medium in response to a hydraulic gradient. Also known as the coefficient of permeability, hydraulic conductivity is a function of the intrinsic permeability of a porous medium and the kinematic viscosity of the water which flows through it. Hydraulic conductivity has units of length per time (cm/sec).

Hydraulic Gradient - the change in piezometric head between two points divided by the horizontal distance between the two points, having dimensions of length per length (cm/cm). See piezometric head.

Hydrocarbon - one of a very large group of chemical compounds composed only of carbon and hydrogen; the largest source of hydrocarbons is from petroleum crude oil.

Infiltration - the downward movement of water through a soil from rainfall or from the application of artificial recharge in response to gravity and capillarity.

Interfacial tension - phenomena occurring at the interface of a liquid and gas where the liquid behaves as it if were covered by an elastic membrane in a constant state of tension. The tension is due to unbalanced attractive forces between the liquid molecules at the liquid surface.

Liquid Density - the amount of mass of a liquid per unit volume of the liquid.

Mobility - the ability of a substance to move into or out of a phase due to physical or chemical processes.

Moisture Content - the amount of water lost from the soil upon drying to a constant weight, expressed as the weight per unit weight of dry soil or as the volume of water per unit bulk volume of the soil. For a fully saturated medium, moisture content equals the porosity; in the vadose zone, moisture content ranges between zero and the porosity value for the medium. See porosity, vadose zone, saturated zone.

Molecular Diffusion - process where molecules of various gases tend to intermingle and eventually become evenly dispersed.

Molecular Weight - the amount of mass in a mole of molecules of a substance determined by summing the masses of the individual atoms comprising the molecule. One mole is equivalent to 6.02×10^{23} molecules.

Non-Aqueous Phase Liquid (NAPL) - contaminants that remain as the original bulk liquid in the subsurface.

Octanol-Water Partition Coefficient (K_{ow}) - a coefficient representing the ratio of solubility of a compound in octanol to its solubility in water. As K_{ow} increases, water solubility decreases.

Partial Pressure - the portion of total vapor pressure in a system due to one or more constituents in the vapor mixture.

Particle Density - the amount of mass of a substance per unit volume of the substance.

Permeability - a measure of a soils resistance to fluid flow. Permeability, along with fluid viscosity and density are used to determine fluid conductivity.

Phase - the physical form in which a substance is found. As discussed in this manual, the three major phases are liquid, vapor and dissolved in pore water.

Piezometric Head - the level to which water from a given aquifer will rise by hydrostatic pressure. For the uppermost unconfined aquifer, the piezometric head is identical to the water table elevation. For confined aquifers, the piezometric head can be above or below the water table.

Porosity - the volume fraction of a rock or unconsolidated sediment not occupied by solid material but usually occupied by water and/or air. Porosity is a dimensionless quantity.

Pressure Gradient - a pressure differential in a given medium, such as water or air, which tends to induce movement from areas of higher pressure to areas of lower pressure.

Refractory Index - a measure of the ability of a substance to be biodegraded by bacterial activity.

Residual Saturation - the amount of water or oil remaining in the voids of a porous medium and held in an immobile state by capillary and dead-end pores.

Retardation - preferential retention of contaminant movement in the subsurface resulting from adsorption processes or solubility differences.

Rip Rap - protective covering, often stone or coarse gravel, for earthen slopes to prevent erosion.

Saturated Zone - as defined in this manual, the zone of the soil in which all space between the soil particles is occupied by water, including the capillary zone.

Soil Sorption Coefficient - a measure of the preference of an organic chemical to leave the dissolved aqueous phase in the soil and become attached or adsorbed to soil particles as organic carbon.

Solubility - the amount of mass of a compound that will dissolve into a unit volume of solution.

Sorption - a general term used to encompass the process of absorption, adsorption, ion exchange, and chemisorption.

Stratigraphy - the study of original succession and age of subsurface layers; dealing with their form, distribution, composition, and physical and chemical properties.

Surfactant - natural or synthetic chemicals that have the ability to promote the wetting, solubilization, or emulsification of various organic chemicals.

Unconfined Aquifer - an aquifer that is under atmospheric pressure. It is usually the uppermost aquifer in the subsurface with its upper limit being the water table.

Unsaturated Zone - the portion of a porous medium, usually above the water table in an unconfined aquifer, within which the moisture content is less than saturation and the capillary pressure is less than atmospheric pressure. The unsaturated zone does not include the capillary fringe.

Upgradient - in the direction of increasing static head.

Vadose Zone - the portion of a porous medium above the water table within which the capillary pressure is less than atmospheric and the moisture content is usually less than saturation. The vadose zone includes the capillary fringe.

Vapor Density - the amount of mass of a vapor per unit volume of the vapor.

Vapor Pressure - the equilibrium pressure exerted on the atmosphere by a liquid or solid at a given temperature. Also a measure of a substance's propensity to evaporate or give off flammable vapors. The higher the vapor pressure, the more volatile the substance.

Viscosity - a measure of the internal friction of a fluid that resists shear within the fluid. The greater the internal friction forces of a fluid (i.e., the greater the viscosity), the less easily the fluid will flow.

Volatilization - the process of transfer of a chemical from the water or liquid phase to the air phase. Solubility, molecular weight, and vapor pressure of the liquid and the nature of the air-liquid/water interface affect the rate of volatilization. See solubility, vapor pressure.

Water Content - see moisture content

Water Table - the water surface in an unconfined aquifer at which the fluid pressure in the voids is at atmospheric pressure.

Weathering - the process where a complex compound is reduced to its simpler component parts, transported through physical processes, or biodegraded over time.

BLANK WORKSHEETS

Table 10. Likelihood of NAPL Being Present on the Water Table

FACTOR	UNITS	SITE OF INTEREST ▼	INCREASING LIKELIHOOD →		
RELEASE- RELATED					
* • **Amount Released**	gal		Small (<1,000) ○	Medium (1000-10,000) ○	Large (>10,000) ○
* • **Rate Of Release**	-		Slow Release ○	- - ○	Instantaneous Release ○
• **Time Since Release**	months		Long (>12) ○	Medium (1-12) ○	Short (< 1) ○
SITE - RELATED					
* • **Preferential Flow Pathways**	-		Not Present ○	Unknown ○	Present ○
* • **Depth To Groundwater**	meters		Deep (>15) ○	Medium (2-15) ○	Shallow (< 2) ○
• **Hydraulic Conductivity (of the Unsaturated Zone)**	cm/sec		Low ($<10^{-5}$) ○	Medium (10^{-5}-10^{-3}) ○	High ($>10^{-3}$) ○
• **Rainfall Infiltration Rate**	cm/day		High (0.2) ○	Medium (0.05-0.2) ○	Low (<0.05) ○
• **Soil Temperature**	°C		Cool (<10) ○	Medium (10 - 20) ○	Warm (>20) ○
• **Soil Sorption Capacity (Surface Area)**	cm^2/g		High (>1) ○	Medium (0.1-1) ○	Low (<0.1) ○
CONTAMINANT- RELATED					
* • **Liquid Viscosity**	cP		High (>20) ○	Medium (2-20) ○	Low (<2) ○
• **Vapor Pressure**	mm Hg		High (>100) ○	Medium (10-100) ○	Low (<10) ○
• **Water Solubility**	mg/L		High (>1000) ○	Medium (100-1000) ○	Low (<100) ○

* CSFs denoted with an asterisk are typically more important than other CSFs

Table 11. Likelihood of Dissolved Contaminants Being Present in the Saturated Zone

FACTOR	UNITS	SITE OF INTEREST ▼	INCREASING LIKELIHOOD →		
RELEASE- RELATED					
* • Amount Released	gal		Small (100) ○	Medium (100-1000) ○	Large (>1000) ○
* • Rate Of Release	-		Instantaneous Release ○	- -	Slow Release ○
* • Time Since Release	months		Short (<1) ○	Medium (1-12) ○	Long (>12) ○
SITE - RELATED					
• Depth To Groundwater	meters		Deep (>15) ○	Medium (2-15) ○	Shallow (<2) ○
• Fluctuating Water Table	-		Steady ○	Moderately Fluctuating ○	Highly Fluctuating ○
• Hydraulic Conductivity (of the Unsaturated Zone)	cm/sec		Low ($<10^{-5}$) ○	Medium (10^{-5}-10^{-3}) ○	High ($>10^{-3}$) ○
* • Rainfall Infiltration Rate	cm/day		Low (<0.05) ○	Medium (0.05-0.2) ○	High (>0.2) ○
• Soil Temperature	°C		Cool (<10) ○	Medium (10-20) ○	Warm (>20) ○
• Soil Sorption Capacity (Surface Area)	m^2/g		High (>1) ○	Medium (0.1-1) ○	Low (>0.1) ○
CONTAMINANT- RELATED					
• Liquid Viscosity	cP		High (>20) ○	Medium (2-20) ○	Low (<2) ○
• Vapor Pressure	mm Hg		High (>100) ○	Medium (10-100) ○	Low (<10) ○
* • Water Solubility	mg/L		Low (<100) ○	Medium (100-1000) ○	High (>1000) ○

* CSFs denoted with an asterisk are typically more important than other CSFs

Table 12. Worksheet for Evaluating the Feasibility of Using Trench Excavation to Contain Floating NAPL

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
• Amount Released	gallons		Large (>500,000) ○	Medium (50,000-500,000) ○	Small (<50,000) ○
• Time Since Release	months		Long (>12) ○	Medium (1-12) ○	Short (<1) ○
SITE - RELATED					
* • Depth to Groundwater	meters		Deep (>5) ○	Medium (1-5) ○	Shallow (<1) ○
• Stability of Soil Formation	-		Unstable ○	-	Stable ○
* • Presence of Interfering Structures	-		Present ○	-	Not Present ○
CONTAMINANT- RELATED					
• Liquid Viscosity	cP		High (>2) ○	Medium (1-2) ○	Low (<1) ○
* • Liquid Density	g/cm^3		High (>1) ○	-	Low (<1) ○

OTHER CONSIDERATIONS

- Trench excavation can generally be implemented quickly.
- Costs for this method are typically lower than for other methods
- Denser than water contaminants cannot typically be contained with trench excavation

* CSFs denoted with an asterisk are typically more important than other CSFs

TABLE 13. Worksheet for Evaluating the Feasibility of Using Pumping Wells to Contain NAPL and/or Dissolved Contaminant in the Saturated Zone

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
• Amount Released	gallons		Small (<50,000) ○	Medium (50,000-500,000) ○	Large (>500,000) ○
• Time Since Release	months		Short (< 1) ○	Medium (1 - 12) ○	Long (>12) ○
SITE - RELATED					
* • Site Stratigraphy	-		Complex ○	- ○	Simple ○
• Depth to Groundwater	meters		Shallow (<5) ○	-	Deep (>5) ○
CONTAMINANT- RELATED					
• Liquid Density	g/cm^3		Low (<1) ○	-	High (>1) ○
• Liquid Viscosity	cP		High (>2) ○	Medium (1 - 2) ○	Low (<1) ○

OTHER CONSIDERATIONS

- Installation of pumping wells can be delayed due to difficulties in delineating well ZOCs.
- Extracted groundwater must often be disposed of or treated.
- This may be the only effective containment method at sites where depth to water table is great.

* CSFs denoted with an asterisk are typically more important than other CSFs

Table 14. Worksheet for Evaluating the Feasibility of Using Vacuum Extraction to Remove Floating NAPL at Your Site

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
SITE - RELATED					
* • **Soil Air Conductivity**	cm/sec		Low ($<10^{-6}$) ○	Medium (10^{-4}-10^{-6}) ○	High ($>10^{-4}$) ○
• **Soil Temperature**	°C		Low (<10) ○	Medium (10-20) ○	High (>20) ○
• **Moisture Content**	% volume		High (>30) ○	Medium (10-30) ○	Low (<10) ○
• **Soil Surface Area**	m^2/g		High (>1) ○	Medium (0.1-1) ○	Low (<0.1) ○
• **Carbon Content**	% weight		High (>10) ○	Medium (1-10) ○	Low (<1) ○
CONTAMINANT- RELATED					
* • **Vapor Pressure**	mm Hg		Low (<10) ○	Medium (10-100) ○	High (>100) ○
• **Water Solubility**	mg/L		High (>1000) ○	Medium (100-1000) ○	Low (<100) ○

OTHER CONSIDERATIONS

- Treatment of contaminant vapors may be required before discharge to atmosphere.

* CSFs denoted with an asterisk are typically more important than other CSFs

Table 15. Worksheet for Evaluating the Feasibility of Using Air Stripping to Treat Extracted Groundwater at Your Site

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
* • Amount Released	gallons		High (<1,000) ○	Medium (1,000-50,000) ○	Large (>50,000) ○
* • Time Since Release	months		Short (<1) ○	Medium (1-12) ○	Long (>12) ○
SITE - RELATED					
• Groundwater Temperature	°C		Low (<10) ○	Medium (10-20) ○	High (>20) ○
• Total Suspended Solids Content of GW	mg/L		High (>20) ○	Medium (5-20) ○	Low (<5) ○
• Total Dissolved Iron and Manganese Content of GW	mg/L		High (>5) ○	Medium (0.2-5) ○	Low (<0.2) ○
CONTAMINANT- RELATED					
* • Vapor Pressure	mm Hg		Low (<10) ○	Medium (10-100) ○	High (>100) ○
* • Water Solubility	mg/L		High (>1000) ○	Medium (100-1000) ○	Low (<100) ○
* • Dissolved Contaminant Concentration	mg/L		Low (<1) ○	Medium (1-100) ○	High (>100) ○

OTHER CONSIDERATIONS

- Air stripping is not effective in removing contaminants to drinking water standards.
- Permitting requirements can delay implementation.
- Can cost effectively treat large volumes of groundwater.
- Treatment of contaminant vapors may be required before discharge to atmosphere.

* CSFs denoted with an asterisk are typically more important than other CSFs

Table 16. Worksheet for Evaluating the Feasibility of Using Carbon Adsorption to Treat Extracted Groundwater at Your Site

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE - RELATED					
• Amount Released	gallons		Large (>50,000) ○	Medium (1,000-50,000) ○	Small (<1,000) ○
• Time Since Release	months		Long (>12) ○	Medium (1-12) ○	Short (<1) ○
SITE - RELATED					
*** • TOC Content of GW**	mg/L		High (>5) ○	Medium (1-5) ○	Low (<1) ○
• Suspended Solids Content of GW	mg/L		High (>20) ○	Medium (5-20) ○	Low (<5) ○
• Total Dissolved Iron and Manganese Content of GW	mg/L		High (>5) ○	Medium (0.2-5) ○	Low (<0.2) ○
CONTAMINANT- RELATED					
*** • Water Solubility**	mg/L		High (>1000) ○	Medium (100-1000) ○	Low (<100) ○
*** • Molecular Weight**	g/mole		Low (<100) ○	Medium (100-200) ○	High (>200) ○

OTHER CONSIDERATIONS

- Can remove contaminants to drinking water standards.
- Costs increase significantly if large volumes or highly contaminated groundwater is encountered.

* CSFs denoted with an asterisk are typically more important than other CSFs

Table 17. Worksheet for Evaluating The Feasibility of Using Biorestoration to Treat Groundwater at Your Site

CRITICAL SUCCESS FACTOR	UNITS	SITE OF INTEREST ▼	SUCCESS LESS LIKELY	SUCCESS SOMEWHAT LIKELY	SUCCESS MORE LIKELY
RELEASE- RELATED					
• Time since release	months		Short (<1) ○	Medium (1-12) ○	Long (>12) ○
SITE- RELATED					
* • Hydraulic Conductivity	cm/sec		Low ($<10^{-5}$) ○	Medium (10^{-3} - 10^{-5}) ○	High ($>10^{-3}$) ○
* • Site Stratigraphy	-		Complex ○	-	Simple ○
• Groundwater temperature	°C		Low (<5) ○	Medium (5-10) ○	High (>10) ○
• pH	pH units		(< 6 or >8) ○		(6-8) ○
CONTAMINANT- RELATED					
• Biodegradability Refractory Index	-		Low (<0.01) ○	Medium (0.01-0.1) ○	High (>0.1) ○
• Total Organic Carbon Content of GW	mg/L		(<10 or >1000) ○	-	(10-1000) ○

OTHER CONSIDERATIONS

- It is difficult to monitor the effectiveness of the system
- Minimizes health risks by keeping contaminants below the ground surface.

* CSFs denoted with an asterisk are typically more important than other CSFs

☆U.S. GOVERNMENT PRINTING OFFICE: 1990 -748-159/20404